September 1

MATERIALS DATA HANDBOOK

Inconel Alloy 718

Edited by

John Sessler
Volker Weiss

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National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

SYRACUSE UNIVERSITY RESEARCH INSTITUTE

DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY

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Contract No. NAS8-11345

DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY
SYRACUSE UNIVERSITY, SYRACUSE, NEW YORK

PREFACE

This Materials Data Handbook on Inconel Alloy 718 was prepared by personnel and associates of the Department of Chemical Engineering and Metallurgy, Syracuse University, as part of a program sponsored by the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama.

It is intended that this Handbook present, in the form of a single document, a comprehensive summary of the Materials property information presently available on this alloy.

The scope of the information included herein includes physical and mechanical property data at cryogenic, ambient and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication and joining techniques. Design data are presented, where available, and these data are complemented with information on the typical behavior of the alloy. The major source for the design data used is the Department of Defense document, Military Handbook-5.

The Handbook is divided into twelve (12) chapters as outlined below:

Chapter	1	General Information
	2	Procurement Information
	3	Metallurgy
	4	Production Practices
	5	Manufacturing Practices
	6	Space Environment Effects
	7	Static Mechanical Properties
	8	Dynamic and Time Dependent Properties
	9	Physical Properties
	10	Corrosion Resistance and Protection
	11	Surface Treatments
	12	Joining Techniques

Information on the alloy is given in the form of Tables and Illustrations supplemented with descriptive text where deemed useful by the authors. Source references for the information presented are listed at the end of each chapter.

ACKNOWLEDGEMENTS

The "Materials Data Handbook, Inconel Alloy 718", was prepared by Syracuse University under Contract No. NAS8-11345 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The program was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the Space Flight Center with Mr. Melvin G. Olsen acting as project manager.

Acknowledgement is made to the following Syracuse University personnel and associates for their contributions to the program.

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The editors are also appreciative of the cooperation extended to the program by members of the Mil-Hdbk-5 committee; personnel of the Defense Metals Information Center (DMIC), Battelle Memorial Institute; personnel of the NASA Marshall Space Flight Center; and to the many individuals and organizations (too numerous to mention) that have contributed to the generation of this document.

John G. Sessler, Editor
Volker Weiss, Associate Editor

* Associate Professor, Dept. of Metallurgical Engineering, Illinois Institute of Technology.

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TABULAR ABSTRACT

Inconel Alloy 718

TYPE:

Wrought, age-hardenable nickel-chromium-iron alloy

NOMINAL COMPOSITION:

Ni-19Cr-19Fe-5Cb-3Mo-0.8Ti-0.6Al

AVAILABILITY:

Sheet, plate, bar, hot-rolled shapes, machined shafts, cold drawn tube and forgings. Castings available as Inconel Alloy 718C.

TYPICAL PHYSICAL PROPERTIES:

Density	8.18 gr/cm^3 at RT (annealed)
Thermal Conductivity	0.027 cal/cm sec C
Thermal Expansion	(20-100C), 13.1 x 10^{-6} in/in/C
Specific Heat	No data found.
Electrical Resistivity	127 microhms-cm at RT (annealed)

TYPICAL MECHANICAL PROPERTIES:

F_{tu}	150,000 psi (annealed)
	190,000 psi (aged)
F_{ty}	90,000 psi (annealed)
	160,000 psi (aged)
e(2 inch)	40 percent (annealed)
	20 percent (aged)
E (tension)	29 x 10^6 psi

FABRICATION CHARACTERISTICS:

Weldability	Excellent if proper procedures are employed.
Formability	Good in annealed condition
Machinability	Good in both annealed and aged conditions.

COMMENTS:

A medium high temperature alloy with exceptionally high tensile and creep properties at temperatures up to about 1300F. Alloy also has good cryogenic properties. Properties and microstructure, however, are strongly influenced by chemical composition and heat treatment.

SYMBOLS

a	One-half notch section dimension
A	Area of cross section; "A" basis for mechanical property values (Mil-Hdbk-5)
Å	Angstrom unit
AC	Air cool
AMS	Aerospace Material Specifications
Ann	Annealed
AUS	Austenitize
Av or Avg	Average
B	"B" basis for mechanical property values (Mil-Hdbk-5)
b	Subscript "bending"
bcc	Body centered cubic
BHN	Brinell hardness number
br	Subscript "bearing"
Btu	British thermal unit (s)
C	Degree (s) Centigrade
c	Subscript "compression"
CD	Cold drawn
CF	Cold finished
cm	Centimeter
c_p	Specific heat
CR	Cold rolled
CW	Cold worked
CVM	Consumable vacuum melted
D or Dia	Diameter
DPH	Diamond pyramid hardness
ϵ	Elongation in percent
E	Modulus of elasticity, tension
E_c	Modulus of elasticity, compression
e/D	Ratio of edge distance to hole diameter
E_s	Secant modulus
E_t	Tangent modulus
ev	Electron volt (s)

F	Degree (s) Fahrenheit
f	Subscript "fatigue"
F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength
fcc	Face centered cubic
FC	Furnace cool
F_{cy}	Compressive yield stress
F_{su}	Shear stress; shear strength
F_{tu}	Tensile ultimate strength
F_{ty}	0.2% tensile yield strength (unless otherwise indicated)
G	Modulus of rigidity
HAZ	Heat affected zone in weldments
hcp	Hexagonal close pack
hr	hour (s)
HT	Heat treat
IACS	International annealed copper standards
in	inch
ipm	inches per minute
K	Stress intensity factor; thermal conductivity
K_c	Measure of fracture toughness (plane stress) at point of crack growth instability
K_{Ic}	Plane strain fracture toughness value
KSI or ksi	Thousand pounds per square inch
K_t	Theoretical elastic stress concentration factor
L	Longitudinal
lb	Pound
LT	Long transverse (same as transverse)
M	Bending moment
m	Subscript "mean"
Max	Maximum
MIL	Military
Min	Minimum
N	Cycles to failure
NSR	Notch strength ratio
NTS	Notch tensile strength

OQ	Oil quench
ppm	Parts per million
pt	Point
r	radius
RA	Reduction in area; Rockwell hardness A scale
RB	Rockwell hardness B scale
RC	Rockwell hardness C scale
ρ (rho)	Density
rpm	Revolutions per minute
RT	Room temperature
SA	Solution anneal
sec	second
S-N	S = stress; N = number of cycles
Spec	Specifications; specimen
ST	Solution treat; short transverse
T	Transverse
t	Thickness; Time, hour
Temp	Temperature
typ	Typical
Var	Variable
VHN	Vickers' hardness number
W	Width
WQ	Water quench

CHAPTER 1

GENERAL INFORMATION

1.1 Inconel Alloy 718 (also known as Inconel 718 and Alloy 718) is a wrought, age-hardenable nickel-chromium base alloy introduced by the Huntington Division of the International Nickel Co., (Inco) in 1959. This alloy was primarily developed for use at medium high temperatures up to 1300F, and to fill a need for a wrought material with good weldability. The sluggish response of the alloy to age hardening permits annealing and welding without spontaneous hardening during heating and cooling. The alloy can be readily welded in the annealed or age-hardened condition, (Refs. 1.1, 1.2 and 1.3).

1.2 Inconel Alloy 718 exhibits exceptionally high yield, tensile, creep and creep rupture strength at temperatures up to 1300F. The alloy also has good properties in the cryogenic temperature range. Its slow aging response is of great benefit in fabrication processes such as forging and forming.

1.3 Typical areas of application for Inconel Alloy 718 are in lightweight welded assemblies in aircraft turbojet engines and for fuel/oxidizer injector plates, forged rings, thrust-chamber jackets, bellows and tubing for liquid oxygen type rocket engines, (Refs. 1.2 and 1.5).

1.4 General Precautions

1.41 Optimum heat treat procedures are dependent upon the chemical composition, particularly the aluminum content.

1.42 The properties and the microstructure of the alloy are strongly influenced by heat treatment and the chemical composition.

CHAPTER 1 - REFERENCES

1.1 "Inconel Alloy 718, Age-Hardenable Nickel-Chromium Alloy", Basic Data, Huntington Alloy Products Div., International Nickel Co., (September 1960)

1.2 H. J. Wagner and A. M. Hall, "Physical Metallurgy of Alloy 718", DMIC Report 217, Battelle Memorial Inst., (June 1965)

1.3 Private Communication with E. B. Fernsler, Huntington Alloy Division, International Nickel Co., (April 1966)

1.4 Current Data Report, "Inconel 718, Age-Hardenable Nickel -Chromium Alloy", Huntington Alloy Division, International Nickel Co., (May 1961)

1.5 Alloy Digest, "Inconel 718, Age-Hardenable Nickel Base Alloy", Filing Code: Ni-65, Engineering Alloys Digest, Inc., (April 1961)

CHAPTER 2

PROCUREMENT INFORMATION

2.1 General. Inconel Alloy 718 is available in the form of sheet, rod, bar, shapes, machined shafts, tube, plate and forgings. Investment castings are also available in the aged condition.

2.2 Procurement Specifications

2.21 NASA Specifications. None.

2.22 Specifications that apply to Inconel Alloy 718 are listed in Table 2.22 for various products.

2.23 Specifications issued for this alloy by a number of companies are listed in Table 2.23.

2.3 Comparison of Specifications. Specifications for Inconel Alloy 718 have been issued by SAE and by a number of companies that intend to use the alloy for different types of applications. These applications are sometimes mentioned in the specifications as indicated in the following quotations from some of these specifications, (Ref. 2.2).

2.31 AMS 5596A. Application: Primarily for parts, such as cases and ducts, requiring high resistance to creep and creep rupture up to 1300F and oxidation resistance up to 1800F, particularly those parts which are formed and then heat treated to develop required properties.

2.32 RBD 170-101 (Rocketdyne). Scope: This material is a nickel-base heat-resistant alloy intended primarily for parts requiring high short-time tensile strength up to 1000F and oxidation resistance to 1800F. It has good cryogenic properties and better weldability than other age-hardenable nickel-base alloys.

2.33 EMS-581c (AiResearch). Application: Primarily for parts requiring high strength and corrosion resistance at both cryogenic and elevated temperatures, particularly those which are machined and welded and then heat treated to develop required properties. Material has good oxidation resistance up to 1800F but is useful at temperatures above 1200F only when stresses are low.

2.34 The properties of the alloy are dependent upon the specific chemical composition and heat treat procedures employed. Thus company specifications are becoming more restrictive regarding chemistry and may require widely differing heat treatments depending upon the particular application.

2.4 Major Producers of the Alloy (United States only), (Ref. 2.4).

2.41 Inconel Alloy 718 was developed by:

Huntington Alloy Products Division
International Nickel Company, Inc.
Huntington, West Virginia 25720

2.42 Other producers, however, have been licensed to produce the composition under their own trade names. Licensees are as follows:

Allegheny-Ludlum Steel Co.
Allvac Metals Co.
Armco Steel Corp.
Cameron Iron Works
Carpenter Steel Co..
Crucible Steel Co. of America
Eastern Stainless Steel Co.
Firth Sterling Co.
Howmet Corp.
Latrobe Steel Co.
Martin Metals Co.
Republic Steel Corp.
Special Metals Corp.
Union Carbide Corp.
Universal-Cyclops Steel Corp.

2.5 Available Forms, Sizes and Conditions

2.51 This alloy is available as mill products in the form of hot rolled and cold rolled sheet, hot rolled plate, hot finished rods and bars, hot rolled shapes, machined shafts, cold drawn seamless tube and forgings. Investment castings are available as Inconel 718C in the aged condition, (Ref. 2.5).

PROCUREMENT SPECIFICATIONS

TABLE 2.22

Source	(Refs. 2.1 and 2.6)
Alloy	Inconel 718
Specification	AMS
Sheet, strip and plate (Solution heat treated at 1750F)	5596A
Sheet, strip and plate (Solution heat treated at 1950F)	5597

COMPANY SPECIFICATIONS

TABLE 2.23

Source	(Ref. 2.2)
Alloy	Inconel Alloy 718
Company	Specification
Aerojet-General	AGC-44152
AiResearch	EMS-581C
General Electric	B50T69-S6
General Electric	C50T79 (S1)
Pratt and Whitney	PWA 1009-C
Rocketdyne	RB0170-101

CHAPTER 2 - REFERENCES

2.1 SAE Aerospace Material Specification, AMS 5596A, Society Automotive Engineering (Revised June 30, 1964)

2.2 H. J. Wagner and A. M. Hall, "Physical Metallurgy of Alloy 718", DMIC Report 217, Battelle Memorial Institute, (June 1, 1965)

2.3 Aerospace Structural Metals Handbook, Vol. II, Non-Ferrous Alloys, V. Weiss and J. Sessler (Editors), ASD-TDR-63-741, (March 1963) Latest revision, March 1966

2.4 Private communication with E. B. Fernsler, Huntington Alloys Division, International Nickel Co., (April 1966)

2.5 Handbook of Huntington Alloys, Huntington Alloy Products Division, International Nickel Co., Inc., Third Edition, (January 1965)

CHAPTER 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of Inconel Alloy 718, in percent, (Ref. 3.4).

Cr	19
Fe	19
Cb + Ta	5.2
Mo	3
Ti	0.8
Al	0.6
C	0.05
B	0.004
Ni + Co	53

3.12 Chemical composition limits, Table 3.1.

3.121 The chemical composition of this alloy differs from that of other nickel-base alloys in its class by the substitution of columbium for much of the aluminum and titanium and the introduction of nearly 20 percent iron. These differences reduce the high temperature capabilities of the alloy but improve its welding characteristics, (Ref. 3.4).

3.122 The chemical composition and heat treatment of the alloy have a marked influence on its properties and microstructure. The complexity of the interrelationship among these factors is still being studied, and specifications for chemical composition and heat treatment have undergone many changes since the alloy was first developed. Specifications on composition are becoming more restrictive, depending upon the particular applications intended for the alloy. The differences between various specifications is mainly in the columbium, aluminum and titanium content and, to a lesser extent, in the carbon and boron content, (Ref. 3.4). Figs. 3.1 and 3.2 show the effect of aluminum content on the room temperature tensile properties of the alloy when annealed at 954C (1750F) and 1066C (1950F), and then aged at various temperatures.

3.2 Strengthening Mechanisms

3.21 General. The alloy is age-hardened by the precipitation of submicroscopic particles, γ' (gamma prime) phase corresponding to $Ni_3(Cb, Mo, Ti)$ or $Ni_3(Cb, Mo, Al, Ti)$. The lattice parameter of the precipitated phase is about 0.8 percent larger than the lattice parameter of the fcc matrix. The resulting coherency strains account for most of the strengthening which occurs. Aging for long times or at higher temperatures transforms the metastable γ' to the orthorhombic Ni_3Cb, which is stable. Conditions for formations of these phases is shown in the isothermal transformation diagram presented in Fig. 3.3 with double aging treatment superimposed. Recent studies by Cometto (see Ref. 3.4) have indicated that this alloy precipitates a metastable γ' phase based on the Ni_3Cb composition, but with a body-centered tetragonal Ni_3V structure. Upon aging at 1400F for 10 hours, furnace cooling at 100 degrees/hour to 1200F, holding 8 hours and air cooling, the lattice constants of the γ' were found to be:

$$a_\circ = 3.624 \text{ Å}$$
$$C_\circ = 7.406 \text{ Å}$$
$$a_\circ/C_\circ = 2.044$$

Both the metastable Ni_3Cb gamma prime and the orthorhombic Ni_3Cb are made up of the same type of atom layers, though apparently they differ in stacking sequence. The transformation to γ' occurs by a simple rearrangement of atoms on existing lattice sites, and occurs rapidly and uniformly because it is not necessary to nucleate a new lattice. The individual gamma prime particles are disc shaped or in the form of platelets, (see Fig. 3.4) and lie on the $\{100\}$ matrix planes. The $C_\circ$ axis of the γ' structure is perpendicular to the plane of the disks. This relationship results in three orientations of γ' particles delineating three $\{100\}$ type gamma planes, (Ref. 3.4).

This analysis can be used to explain the reason why double-aging results in higher strength than single aging. Apparently, to get maximum strengthening, it is necessary to precipitate as much γ' as possible without overaging; that is without transforming from the bcc tetragonal γ' to the orthorhombic Ni_3Cb.

High temperatures and long times favor the latter situation. A more detailed discussion of this subject may be found in Refs. 3.4 and 3.6. It is indicated that more investigations of the complex interractions in the alloy need to be conducted before a full understanding of the mechanisms involved can be obtained.

3.22 Heat Treatment. High strength in the alloy is developed by a high temperature annealing treatment, followed by a lower temperature aging treatment. The prescribed heat treatments to develop desired characteristics of the material have been modified considerably since its introduction. When first introduced, an annealing temperature of 954C (1750F) was recommended. Users were cautioned not to use annealing temperatures exceeding 982C (1800F). Since then, controversy has developed on what constitutes the best heat treatment. Now, annealing temperatures from 954C to 1066C (1750F to 1950F) are commonly used.

It appears that optimum heat treatment procedures are dependent upon the chemical composition and on the specific properties desired. The heat treatments recommended by the International Nickel Co. are given below.

3.221 For Optimum Tensile Properties (where stress rupture notch ductility is not required). All product forms:

Anneal 1950F, 1 hour, air cool

Age 1400F, 10 hours, furnace cool at 100F/hr to 1200F, hold 8 hours, air cool, (Ref. 3.10).

3.222 For Optimum Creep-Rupture Properties. All product forms:

Anneal 1750 to 1800F, 1 hour, air cool

Age 1325F, 8 hours, furnace cool at 100F/hr to 1150F, hold 8 hours, air cool, (Ref. 3.10).

3.223 Typical heat treatments according to AMS and several company specifications, Table 3.2.

3.224 The alloy contracts slightly during the aging process at a linear contraction rate of about 0.001 inch per inch, (Ref. 3.9).

3.225 The alloy is susceptible to sulfur embrittlement or attack by elements such as lead, bismuth, etc. It is therefore essential that all foreign material such as grease, oils, paints, etc. be removed by suitable solvents prior to heat treatment, (Ref. 3.9).

3.3 Critical Temperatures

3.31 Melting range. Melting begins at approximately 2250F, (Ref. 3.4).

3.4 Crystal Structure. The crystallographic structure of Inconel Alloy 718 is quite complex due to the various interactions that take place in this alloy during its production and heat treatment. The metastable gamma prime (γ') strengthening phase is similar in many ways to the face-centered-cubic matrix gamma (γ) phase from which it forms. It is reported (Ref. 3.4) that this precipitated gamma prime phase is based on the orthorhombic Ni_3Cb composition, but has a body-centered tetragonal Ni_3V structure. Carbides (Cb, Ti) have been identified and also a Laves phase (cast material) which has been found to be isomorphous with Fe_2(Cb, Ti), (Ref. 3.12).

3.5 Microstructure. The microstructure of Inconel Alloy 718 is strongly influenced by composition and heat treatment. The cast structure contains a Laves phase in addition to dendrites in the matrix. The Laves phase in the cast structure has been identified with the phenomenon of "freckles", a condition which apparently is detrimental to yield strength and ductility. Studies by Barker (Ref. 3.13) have indicated that this phase in the cast structure is not affected by solution treatment at temperatures below 2100F. It appears that it can be dissolved at 2100F or above. Eiselstein (Ref. 3.11) has indicated that the Laves phase will also appear after long time exposure to relatively high temperatures. The typical "as-cast" structure, showing the Laves phase is presented as Fig. 3.5.

Wrought bar has a microstructure typical of wrought nickel-base alloys. Aging of the annealed structure at temperatures from 1300 to 1400F precipitates the γ' phase which is not visible in the optical microscope. After overaging, this phase transforms to the stable orthorhombic Ni_3Cb, (Ref. 3.4). Fig. 3.6 shows the alloy structure after solution treating and single aging. The stable Ni_3Cb phase has precipitated at the grain boundaries. Fig. 3.7 shows the microstructure when the alloy is slow cooled from a high solution treat temperature (2100F). The microstructure of Inconel Alloy 718 is discussed in greater detail in Ref. 3.4.

3.6 Metallographic Procedures

3.61 Macro-specimens. The degree of surface preparation is largely dependent upon the nature of the examination and the type of etchant to be employed. Rough grinding on an abrasive wheel is usually adequate for small samples. Large specimens may be prepared on a surface grinder. Recommended solutions for macro-etching are given in Table 3.3. Macro-etching can be hastened by warming the sample with hot water prior to etching. Large samples may be conveniently handled by making a raised rim or dam around the edges with plastic tape and then flooding the surface with the etchant, (Ref. 3.15).

3.62 Micro-specimens. A suitable specimen, either unmounted or mounted in plastic with a flat surface is prepared as follows, (Ref. 3.15):

A. Grinding - Hand or power-driven disk grinders carried through a series of emery papers of successively increasing fineness. Commonly used papers are Nos. 3, 2, 1, 0, 00, 000. Each successive grind should be at right angles to the preceding cut and should remove all scratches left by the preceding (courser) grit.

B. Rough polishing - Specimens ground through No. 000 paper may be wet polished on a broadcloth covered wheel, using levigated alumina (particle size about 5 microns) suspended in water. A much faster method utilizes a silk or nylon covered wheel impregnated with diamond dust paste (particle size about 3 microns). If this method is employed, preparation need only consist of grinding through No. 1 paper, thereby eliminating three grinding steps.

C. Final polishing - Fine scratches are removed on a microcloth or duracloth covered wheel using a gamma alumina powder (less than 0.1 micron size) suspended in water, (Ref. 3.15).

D. Etching. The recommended solution for micro-etching of Inconel Alloy 718 samples is given in Table 3.4.

CHEMICAL COMPOSITION LIMITS FOR INCONEL ALLOY 718

TABLE 3.1

Source	(Ref. 3.1) AMS 5596A		(Ref. 3.2) Inco		(Ref. 3.3) G.E.		(Ref. 3.5) Aerojet	
Element	Percent		Percent		Percent		Percent	
	Min	Max	Min	Max	Min	Max	Min	Max
Nickel (a)	50.00	55.00	50.0	55.0	50.00	55.00	50.00	55.00
Chromium	17.00	21.00	17.0	21.0	17.00	21.00	17.00	21.00
Columbium (b)	5.00	5.50	4.5	5.75	4.75	5.50	4.75	5.50
Molybdenum	2.80	3.30	2.8	3.3	2.80	3.30	2.80	3.30
Titanium	0.65	1.15	0.3	1.3	0.70	1.40	0.65	1.40
Aluminum	0.40	0.80	0.2	1.0	0.20	0.80	0.10	0.80
Carbon	0.03	0.10	-	0.10	-	0.10	-	0.10
Boron	0.002	0.006	-	-	0.002	0.010	0.001	0.01[illegible]
Cobalt (c)	-	1.00	-	-	--	1.00	-	1.00
Manganese	-	0.35	-	0.50	-	0.35	-	0.45
Silicon	-	0.35	-	0.75	-	0.45	-	0.45
Copper	-	0.10	-	0.75	-	0.75	-	0.30
Phosphorus (d)	-	0.015	-	-	-	0.015	-	0.01[illegible]
Sulfur	-	0.015	-	0.03	-	0.03	-	0.01[illegible]
Tantalum	-	-	-	-	-	1.00	-	-
Iron	Balance		Balance		Balance		Balance	

(a) Plus cobalt

(b) Plus tantalum

(c) If determined

(d) If specified

TYPICAL HEAT TREATMENTS FOR ALLOY 718

TABLE 3.2

Source	(Ref. 3.4)				
Alloy	Inconel Alloy 718				
Specification Identification	Company	Ann Temp, F	First Aging Temp, F	Second Aging Temp, F	Aging Method (a)
AMS 5596A	Society of Automotive Engineers	1750	1325	1150	I or II
AMS 5597A		1950	1400	1200	
B50T69-S6	General Electric Company	1700	1325	1150	I
C50T79(S1)	General Electric Company	1800	1325	1150	I
PWA 1009-C	Pratt and Whitney Aircraft	1750	1325	1150	I or II
EMS-581c	AiResearch	1950	1350 (b)	1200	I
RB0170-101	Rocketdyne	1950	1400	1200	III
AGC-44152	Aerojet-General	1950	1350	1200	IV

(a) I: Hold 8 hours at first aging temperature, furnace cool at 100°/hr to second aging temperature. Hold 8 hours, air cool.

II: Hold 8 hours at first aging temperature, furnace cool to second aging temperature. Hold at second aging temperature until total time elapsed since the beginning of the first aging is 18 hours.

III: Hold 10 hours at first aging temperature, furnace cool to second aging temperature. Hold at second aging temperature until total time elapsed since the beginning of the first aging is 20 hours.

IV: Same as II, but first aging time may be 8 to 10 hours.

(b) 1400F on certain heavy forgings.

ETCHING SOLUTIONS FOR REVEALING MACROSTRUCTURE

TABLE 3.3

Source	(Ref. 3.15)	
Solution	Composition (a)	Remarks
Lepito's	15g$(NH_4)_2$ SO_4 in 75ml H_2O 250g $FeCl_3$ in 100 ml HCl, mix and add 30 ml HNO_3	Etching time 30-120 seconds Macro-etch for general surface and weld structure.
Hydrochloric-Peroxide	H_2O_2 (30%) 1 part HCl 2 parts H_2O 3 parts	Must be freshly mixed. Use hot water to speed reaction. Any stains formed may be removed with 50% HNO_3. Macro-etch for revealing grain structure.

(a) Use concentrated acids.

ETCHING SOLUTION FOR REVEALING MICROSTRUCTURE

TABLE 3.4

Source	(Ref. 3.15)	
Solution	Composition (a)	Remarks
Chromic Acid	CrO_3 5g H_2O 100ml	Electrolytic micro-etch for grain boundaries. Use 0.2 to 0.5 amps/sq cm current for 30 to 50 seconds. Specimen is anode with a platinum or Inconel 600 cathode.

(a) Use concentrated acids.

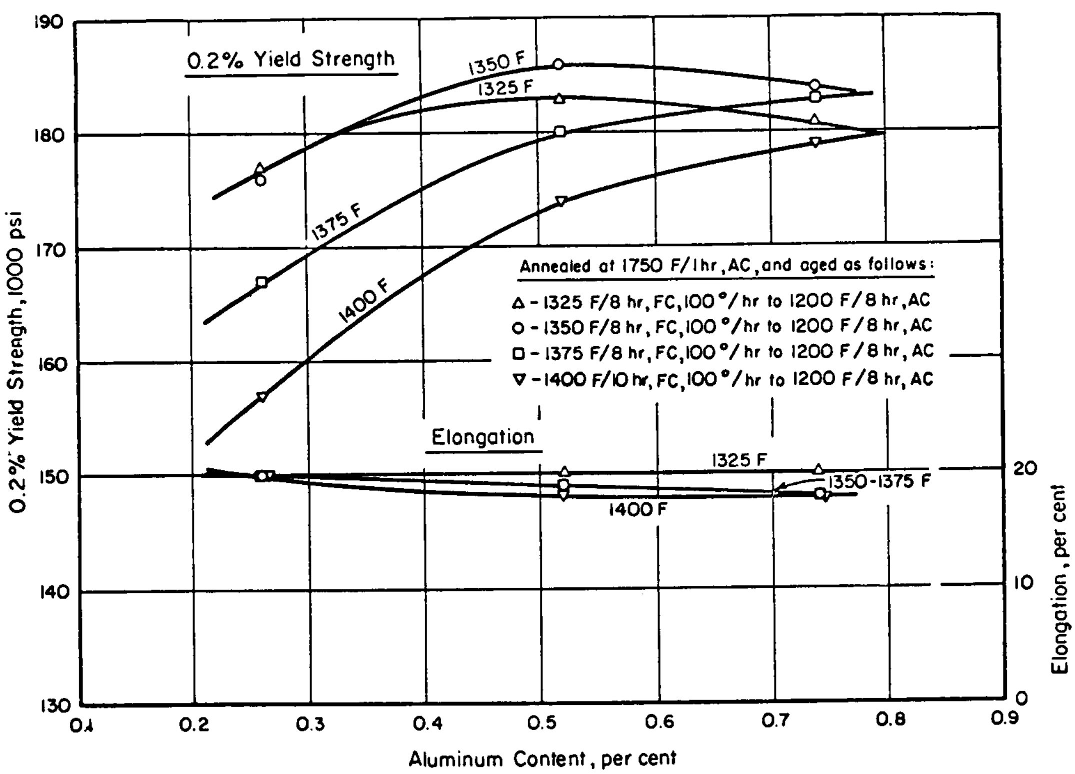


FIG. 3.1 EFFECT OF ALUMINUM CONTENT ON ROOM TEMPERATURE YIELD STRENGTH OF HOT ROLLED BAR STOCK ANNEALED AT 1750F

(Ref. 3.4)

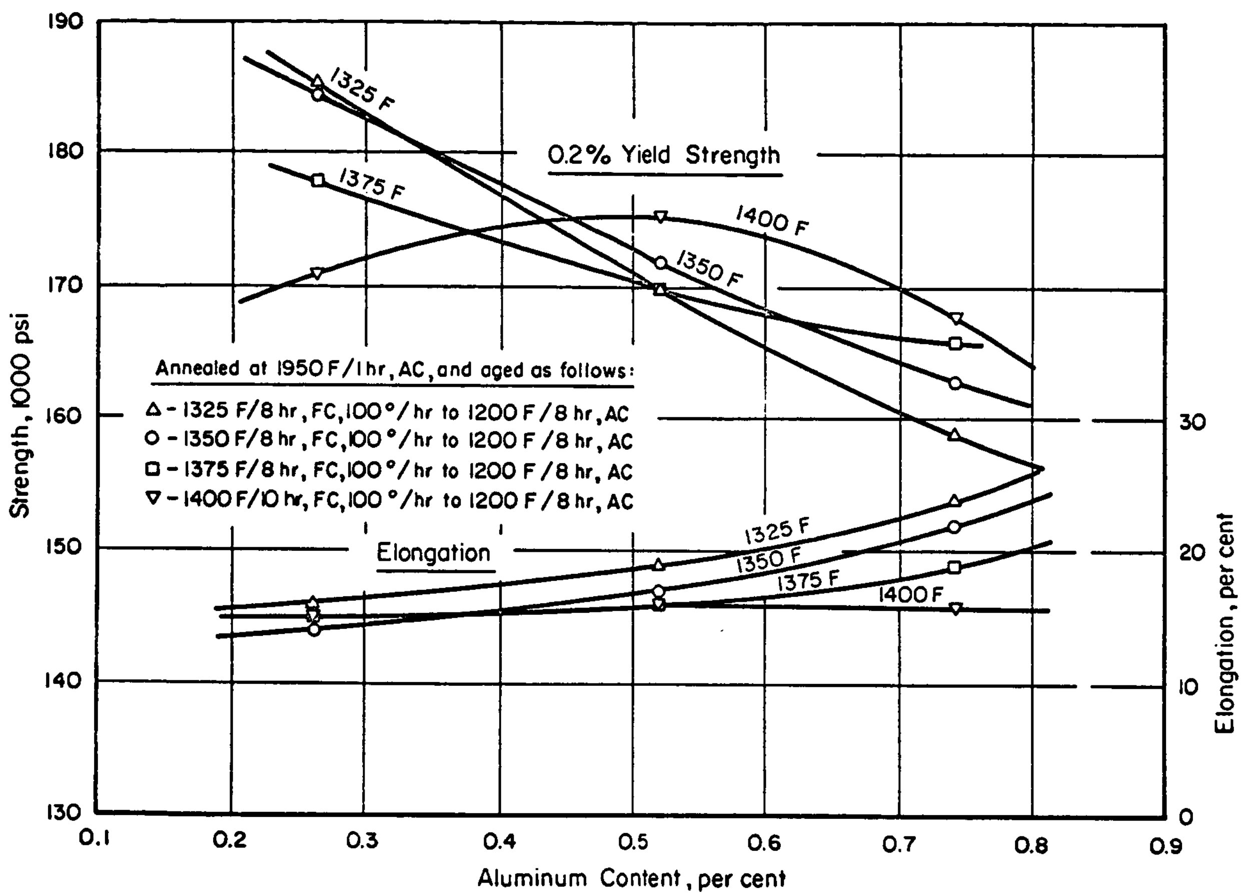


FIG. 3.2 EFFECT OF ALUMINUM CONTENT ON ROOM TEMPERATURE YIELD STRENGTH OF HOT ROLLED BAR STOCK ANNEALED AT 1950F

(Ref. 3.4)

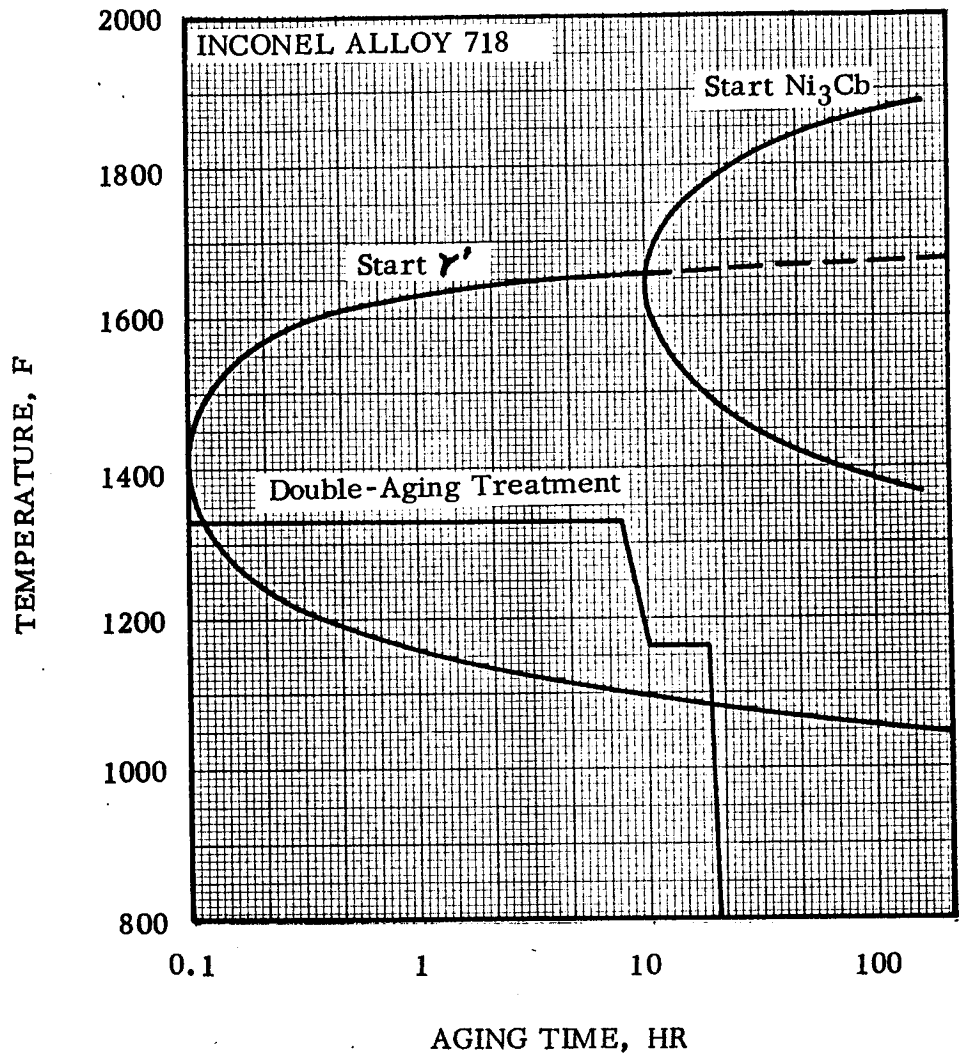
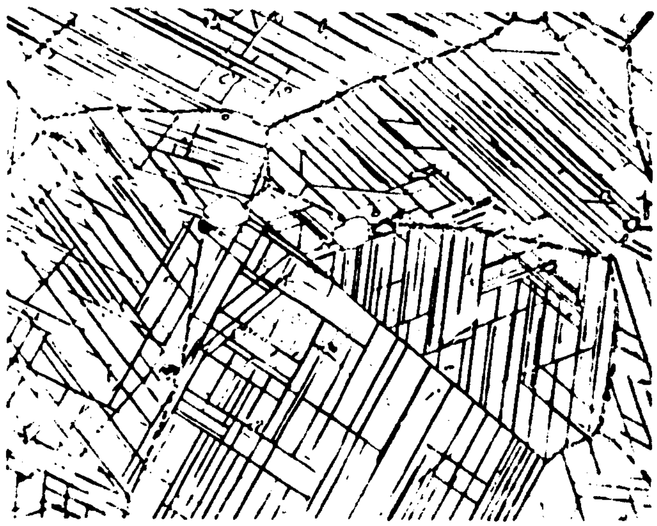


FIG. 3.3 ISOTHERMAL TRANSFORMATION DIAGRAM FOR GAMMA PRIME AND Ni_3Cb PHASES; WITH DOUBLE-AGING TREATMENT SUPERIMPOSED

(Ref. 3.11)



1000X **5% Chromic Acid Etch**

Annealed: 2100F, 1 HR, WC plus
Aged: 1600F, 100 HR, AC

FIG. 3.4 MICROSTRUCTURE OF ALLOY SHOWING WIDMÄNSTATTEN NEEDLE PATTERN WITH SMALL BACKGROUND GAMMA PRIME PRECIPITATE
(The needle-like phase is Ni_3Cb)

(Ref. 3.11)

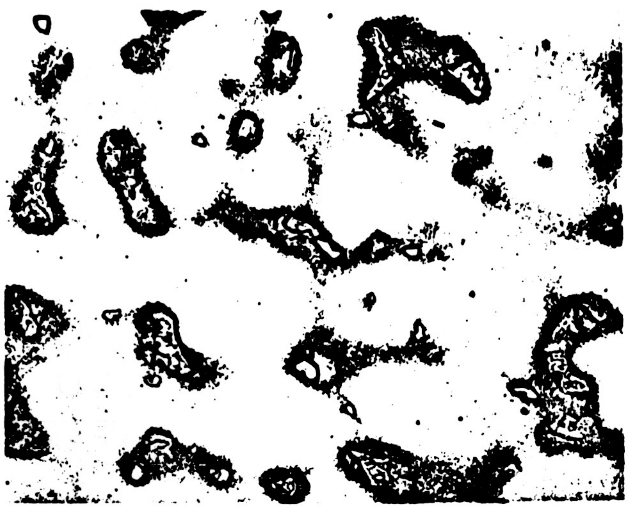
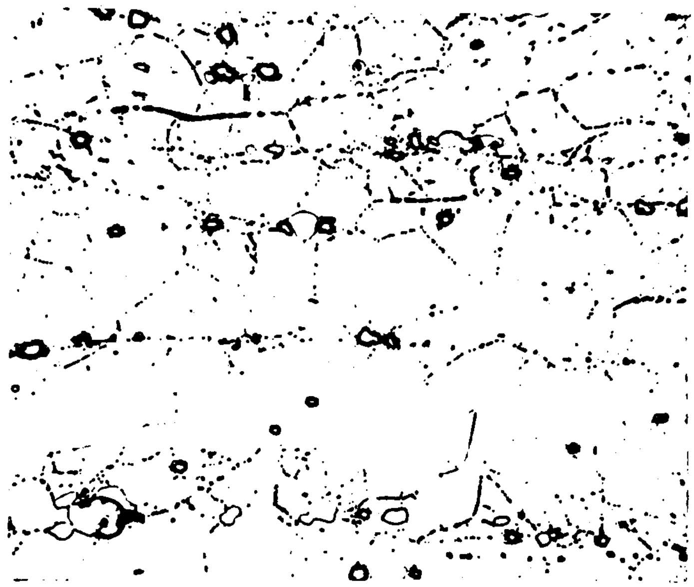


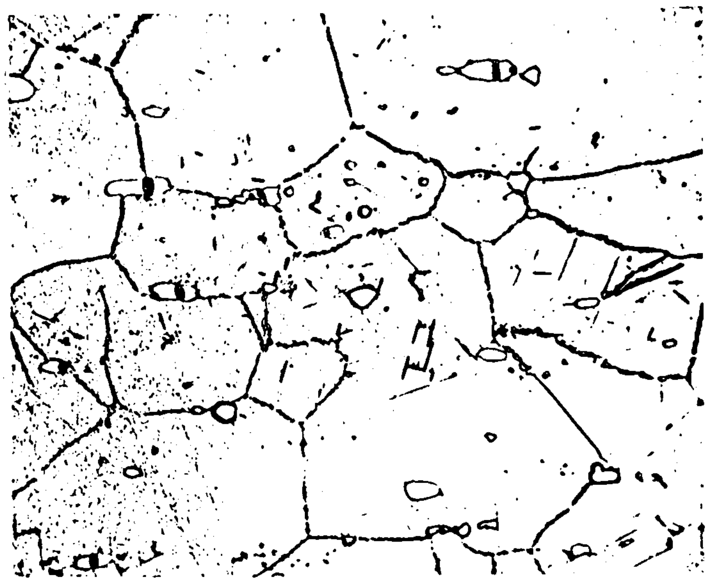
FIG. 3.5 TYPICAL "AS CAST" STRUCTURE (Irregular white phase is Laves)

(Refs. 3.12 and 3.13)



Etchant: 92% H_2SO_4 500X
5% HCl
3% HNO_3
Annealed: 1800F, 1 HR, AC, plus
Aged: 1325F, 16 HRS, AC

FIG. 3.6 MICROSTRUCTURE OF SINGLE AGED SAMPLE
(Ni_3 Cb has precipitated at the grain boundaries)
(Ref. 3.9)



Etchant: 92% H_2SO_4 500X
5% HCl
3% HNO_3

FIG. 3.7 MICROSTRUCTURE OF ALLOY COOLED AT 5 DEGREES PER MINUTE FROM 2100F. Fe_2 (Cb Ti) HAS PRECIPITATED AT GRAIN BOUNDARIES. ANGULAR DISPERSED PARTICLES ARE NITRIDES AND CYANONITRIDES OF Ti, Cb (Ref. 3.9)

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3.7 Current Data Report - Inconel 718, International Nickel Co., Huntington Alloy Products Div., (May 1961)

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3.9 E. H. Schmidt, "Correlation of Experimental Data for Fabrication of Inconel 718", Rocketdyne, Div. of North American Aviation, Inc., Lab. Rep. No. RD 62-10, (July 1962)

3.10 Personal Communication with Mr. E. B. Fernsler, Huntington Alloy Products Div., International Nickel Co., (April 1966)

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3.12 M. Kaufman and A. E. Palty, "Phase Structure of Inconel 718 and 702 Alloys", Transactions, AIME, Vol. 221, (1961), p. 1253

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3.15 Handbook of Huntington Alloys, Huntington Alloy Products Division, International Nickel Co., Third Edition, (January 1965)

3.16 A. M. Sabroff et al., "A Manual on Fundamentals of Forging Practice", Supplement to ML-TDR-64-95, Battelle Memorial Institute, (December 1964)

CHAPTER 4

PRODUCTION PRACTICES

4.1 General. Production practices that are considered to be conventional for heat resistant alloys are used in the production of Inconel Alloy 718 mill products, (Ref. 4.2). These practices are very similar to those used for the production of stainless steel products in wrought forms. Primary deformation processes such as rolling, forging, extrusion and drawing are employed to reduce an ingot or billet to a standard mill product (eg. sheet, plate, bar, tube, etc.). Hot working temperatures are generally higher than the temperatures used for steel because the nickel-base alloys retain their strength to higher temperatures.

4.2 Manufacture of Wrought Products

4.21 Melting. An important factor in the production of high quality wrought products is the making of a good casting in the form of an ingot. The ingot will not be sound unless the melting procedures are carefully controlled. The Inconel Alloy 718 is always vacuum melted. Procedures employed include (a) induction melting in air followed by consumable arc remelting, (b) vacuum induction melting (sometimes followed by consumable arc remelting or double-vacuum induction melting). Vacuum-induction melting prevent uncontrolled losses of easily oxidized elements (such as Ti and Al), removes gaseous impurities and permits stricter control of final composition. All of these factors result in more consistent properties than are obtained by air melting. Also, consistently better 100 hour creep-rupture strength is usually obtained over the entire temperature range of importance by employing vacuum melting techniques.

Consumable electrode vacuum-arc melting volatizes impurities and also breaks down and disperses non-metallic inclusions. Segregation and unsoundness at the center of the ingot are reduced and this results in improved hot working characteristics, particularly when vacuum-induction-melted ingots are employed as electrodes for remelting by the consumable electrode process, in vacuum, (Refs. 4.1, 4.2, and 4.3).

4.22 After solidification, the cast ingots are converted to wrought products by conventional methods that are normally used for the working of nickel-base alloys. The high temperature strength of these alloys, however, requires that equipment for hot working must be more powerful than for equivalent sections of carbon steel. The lower temperature limit of the hot working range is usually determined by the limitations of the equipment and the upper limit must be safely below the melting point. The hot working range is very narrow so that frequent reheating is necessary during the ingot breakdown.

Ingots are conventionally reduced to blooms, billets or large bars by the use of steam driven cogging hammers, vertical presses or blooming mills. Extrusion is also being used to a limited extent. After the cogging operation and prior to further work or finishing, the billet is "conditioned" to remove surface defects. Common conditioning methods are swing-frame grinding, scarfing (gouging with a burning oxygen stream) or machining. Heat resistant alloys are relatively difficult to scarf unless a flux is added to the oxygen stream, since the metal does not burn out spontaneously as in the case of carbon steel. Sometimes grinding or scarfing is done "hot" while the billet is being cogged. Cracks may develop which would prevent further working unless it is removed immediately. Conditioning by machining is faster than grinding, but has the disadvantage that sound metal is also removed along with the defective areas, whereas in swing-frame grinding a skillful operator can confine his efforts primarily to the areas that need attention, (Refs. 4.1 and 4.2).

4.23 Many types of finishing processes are employed in the production of heat resistant alloys. After conditioning, blooms and billets are reduced to bars, rounds, squares or flats on hot rolling mills. Subsequent to the rolling process, bar sections are usually stress relieved or heat treated and given a final processing by pickling, cold drawing, centerless grinding or a combination of these processes. Plate, sheet and strip are produced in a conventional manner, usually on "hand" mills where the work is passed through the rolls and then back over the rolls by hand. A great deal of flexibility is inherent in this process, (Ref. 4.1). The primary deformation processes (rolling, extrusion, forging and drawing) used for the production of nickel-base alloy mill product forms are discussed in considerable detail in Ref. 4.5.

4.3 Cast Products. Although Inconel Alloy 718 is used primarily in wrought forms, the alloy is also used in the form of castings, (eg. engine frames). The casting composition is essentially the same as that of the wrought alloy and it is usually vacuum melted to maintain cleanliness, (Ref. 4.4).

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CHAPTER 5

MANUFACTURING PRACTICES

5.1 General. The slow aging response of Inconel Alloy 718 is beneficial in the fabrication of the alloy. Distortion of fabricated assemblies is kept at a minimum and formability is maintained at a high level because low annealed hardness can be obtained by air cooling from the annealing temperatures. It is reported (Ref. 5.1) that strain-age cracking is practically non-existent in this alloy because of its sluggish aging response. Forgeability of the alloy is reported to be as good as that of V-57 for blades and of Waspaloy for wheels, (Ref. 5.1).

5.2 Forming. Nickel-base alloys have been fabricated both by primary and secondary forming techniques that are similar to those used for the forming of stainless steels. Primary deformation processes are those designed to reduce ingots or billets to standard mill product forms and these include processes such as rolling, forging, extrusion and drawing. Mill products may be converted to more useful shapes by secondary deformation processes. All of the conventional techniques used for this purpose have been applied successfully to nickel-base alloys including the following:

Brake bending
Deep drawing
Spinning and shear forming
Drop hammer forming
Trapped-rubber forming
Stretch forming
Tube forming
Roll forming and bending
Dimpling
Joggling
Blanking
Sizing

Most nickel-base alloys can be worked at both room and elevated temperatures. The hot working temperatures are generally higher than those used for steel because these alloys retain their strengths to higher temperatures. The ductility of most nickel-base alloys compares with that of stainless steels at room temperature. Thus secondary working can usually be performed with conventional processing techniques. Ref. 5.4 is recommended as an excellent state-of-the-art summary of the present status of deformation processing of nickel-base alloys.

Comprehensive information on the forming characteristics of Inconel Alloy 718 do not appear to be available. However, studies at McDonnell Aircraft Corp. (Ref. 5.2) have indicated that the alloy has good formability characteristics in the annealed condition. These studies included total elongation, uniform elongation and bend tests. Also, Guerin Rubber Forming and Impact Rubber forming methods were used to form 0.048 inch specimens on a stretch flange radius of 6.05 inches and a shrink flange radius of 9.95 inches. These specimens were formed around a 0.090 inch bend radius. Various flange lengths were formed to determine the amount of flange distortion that would result from each configuration. It was found that both forming methods resulted in formed parts with very nearly the required production tolerances. A minimum amount of restriking and hand working would be necessary to smooth out any deformities to produce parts to production tolerances. It was concluded that the alloy in the annealed condition was readily formable using standard production rubber forming methods. Typical results of the forming tests are given in Table 5.1.

Bend tests on 0.048 inch annealed sheet indicated a minimum bend radius of 0.031 inch for specimens bent perpendicular to the rolling direction and 0.047 inch for specimens bent parallel to the rolling direction of the sheet, (Ref. 5.2).

Examples of the types of failures usually encountered in various sheet forming processes are shown in Table 5.2.

5.3 Forging. Hot working of Inconel Alloy 718 is performed in the range of temperatures from 2100F down to 1800F. In this range, the alloy has high strength (F_{ty} = 16,000 psi) and offers considerable resistance to deformation during hot working. Thus, the forces required for forging of the alloy are somewhat higher than those required for most other nickel-base alloys. In the last operation the metal should be worked uniformly with a gradually decreasing temperature, finishing with some reduction in the 1800-1850F range. This hot-cold work helps to improve the strength of the forging, (Ref. 5.3).

Care should be taken to avoid overheating the metal by heat buildup due to working. The piece should be reheated when any portion has cooled below 1800F. Air cooling is preferred to water quenching after forging, (Ref. 5.3).

All tools and dies should be preheated to about 400-500F to avoid chilling the metal. The stock should be charged into a furnace controlled at 2025 to 2075F. The metal should be placed on clean steel rails or in a sulfur free refractory and should be protected against contamination from foreign materials. Fuels used should be low in sulfur content.

The forging stock is brought up to temperature and soaked long enough to insure uniformity, then pulled from the furnace. Prolonged soaking, while not too harmful, is not preferred. To avoid duplex or germinated grain structure, the material should be uniformly reduced. If possible, a final reduction of 20 percent minimum should be used for open die work and 10 percent for closed die practices.

If ruptures appear on the surface during forging, they must be removed at once; either by hot grinding or cooling the work and cold overhauling. When upsetting rod stock, the edges should be given a 1/4 inch chamfer or radius to prevent localized chilling. This also avoids the formation of a ring like impression on the faces of the upset disk, (Ref. 5.3).

During forging of nickel-base alloys, a lubricant is necessary between the part and die to reduce their natural tendency to seize and gall. Lubricants containing sulfur are undesirable. Commonly used lubricants are mixtures of graphite and oil, but materials such as glass, mica, sawdust and asbestos have also been used with varying degrees of success, (Ref. 5.4).

5.4 Machining. The alloy is readily machined in the annealed or the age-hardened condition. The aged material gives better chip action on chip-breaker tools and produces a better finish. The annealed condition, however, will give a slightly longer tool life and requires slightly less power than is required for Inconel Alloy X-750.

The recommended speeds for machining the alloy with high speed steel tools are given in Table 5.3. Typical lathe turning tool dimensions are presented in Table 5.4.

Drills should be ground with 130 to 135 degree included point angle. For reaming, narrow land reamers ground to a 30 degree angle chamfer and a 5 to 10 degree face rake are recommended. Standard milling cutters with 5 degree (primary) and 10 degree (secondary) relief back of the cutting edges, to prevent drag, may be used. For thread tapping standard taps ground to a hook angle of about 7 to 10 degrees have been used successfully. Threads can be chased with tangent, milled or hobbed type insert thread chasers ground to 15 degree rake, 5 degree relief and 20 degree throat angle.

Chlorinated sulfurized oils should not be used when drilling, form cutting or reaming. For general turning, a water-base chemical coolant is recommended. Oils and coolants should be removed completely prior to any heating operations, (Ref. 5.3).

TABLE 5.1

Source	(Ref. 5.2)	
Alloy	Inconel Alloy 718 (Annealed)	
Operation	Flange Length	Remarks
7000 ton Hydropress	1.40 stretch flange 0.86 shrink flange	Three wrinkles in shrink flange, diagonal buckle in stretch flange ends
7000 ton Hydropress 1/2 inch hard lead overlay with 5 soft lead straps (a)	1.40 stretch flange 0.86 shrink flange	No wrinkles in either flange; slight web warpage
Impact rubber formed 1/2 inch hard lead overlay	1.40 stretch flange 0.86 shrink flange	Slight web warpage; slight wrinkling of shrink flange and at ends of stretch flange
Impact rubber formed Soft lead strip overlay at shrink flange Restrike without overlay	1.60 stretch flange 1.06 shrink flange	Slight web warpage Small wrinkles present in shrink flange Slight warpage at one end of stretch flange
Impact rubber formed 1/2 inch hard lead overlay Reduced heavy shrink flange wrinkles by hand forming with soft lead straps Restrike 2 times Repeat above	1.60 stretch flange 1.06 shrink flange	Slight wrinkles not completely removed by hand working and restriking operations

(a) The hard lead overlay consisted of lead alloyed with 6% antimony.

TYPES OF FAILURE IN SHEET-FORMING PROCESSES

TABLE 5.2

Source	(Ref. 5.6)	
Process	Cause of Failure	
	Splitting	Buckling
Brake forming	x	
Dimpling	x	
Beading		
Drop hammer	x	
Rubber press	x	
Sheet stretching	x	
Joggling	x	x
Liner stretching	x	x
Trapped rubber, stretching	x	x
Trapped rubber, shrinking		x
Roll forming		x
Spinning		x
Deep drawing		x

TYPICAL LATHE TURNING TOOL DIMENSIONS

TABLE 5.3

Source	(Ref. 5.3)	
Alloy	Inconel Alloy 718	
Operation	Grind Lathe Turning Tool	
Type of Tool	High Speed Steel	Cemented Carbide
Back rake angle	8 to 10 degrees	0 to 4 degrees positive
Side rake angle	10 to 20 degrees	8 degrees positive
End relief angle	7 degrees	5 to 7 degrees (P) 8 to 10 degrees (S)
Side relief angle	7 degrees	5 to 7 degrees (P) 8 to 10 degrees (S)
End cutting edge angle	8 to 10 degrees	8 to 10 degrees
Side cutting edge angle	15 to 30 degrees	15 to 30 degrees
Nose radius	1/32 inch	0.010 to 0.032 inch

(P) Primary

(S) Secondary

RECOMMENDED SPEEDS FOR MACHINING WITH HSS TOOLS

TABLE 5.4

Source	(Ref. 5.3)			
Alloy	Inconel Alloy 718			
Turning (a)(b)(f)	Drilling (a)(c)	Reaming (a) (d)	Milling (a)(e)	Threading and Tapping (a)
15-20	15-20	7-14	15-20	5-8

(a) Speeds given are in FPM (feet/min).

(b) Use roughing feeds of 0.010 to 0.015 inch/revolution. Finish feeds are governed by the desired finish.

(c) Use feeds proportional to drill diameter:
1/16 to 1/4 inch diam. - 0.0005 to 0.002 inch/revolution
1/4 to 3/4 inch diam. - 0.002 to 0.004 inch/revolution
3/4 to 2 inch diam. - 0.004 to 0.006 inch/revolution

(d) Reaming feeds are about three times that used for a drill of the same size.

(e) Use a feed of 0.003 to 0.006 inch/tooth.

(f) Operate at 60 to 100 FPM with cemented carbide tools with feeds of 0.005 to 0.015 inch/revolution. Grade C-2 tools are suitable.

CHAPTER 5 - REFERENCES

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CHAPTER 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Nickel-base alloys are used successfully in both structural and non-structural applications for launch vehicles and spacecraft. In general, these alloys are relatively insensitive to degradation under typical space environment conditions. The vapor pressures of these alloys are sufficiently high, (Fig. 6.1), so that the combined temperature-vacuum effects are negligible. Nuclear and space indigenous radiation induced defects do not appear to significantly affect mechanical and physical properties, at room ambient and elevated temperatures, below accumulated doses of about 1×10^{19} neutrons/cm^2 or greater, (Ref. 6.2). At these high doses, slight embrittlement takes place, resulting in increases in hardness and in some physical properties and a decrease in creep rate. Fatigue properties do not appear to be affected significantly. When irradiated at cryogenic temperatures, the dose threshold may be lowered by one or two decades, but the probabilities of encountering doses on this order of magnitude are extremely remote except in the vicinity of nuclear reactors.

Elevated temperatures, hard vacuums, high energy radiations, and micrometeoroids can individually and collectively influence the surface characteristics of nickel-base alloys by desorption processes and erosion. These phenomena are of importance if optical properties, lubrication, certain electrical properties, etc. are critical design parameters. Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. The sputtering process is associated with a minimum threshold energy value for atomic or molecular particles striking a material surface. Typical values which have been obtained for this threshold energy are 6, 11 and 12 ev or O, N_2 and O_2 particles, respectively, to remove one or more atoms from the materials surface upon which they impinge, (Ref. 6.3). Loss of metal by this mechanism can vary over a wide range and the greatest loss may be expected during solar storms, (Ref. 6.4). However, loss of metal by sputtering has little structural significance, although it may seriously affect optical and emissive properties of the material surface. Estimates of surface erosion by sputtering are presented in Table 6.1.

Micrometeoroids can produce surface erosion similar to sputtering but on a more macroscopic scale, and may also produce punctures. They vary widely in mass, composition, velocity and flux; generalizations about rates of erosion and penetration, therefore, must be used with care. The predicted frequency of impact as a function of meteoroid mass is given in Fig. 6.2.

The surface erosion of nickel-base alloys due to corpuscular radiation is probably insignificant, amounting to something in the order of 10 μ per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films on these alloys. The removal of such films might result in loss of lubricity and an increased propersity to "cold weld". The interaction of indigenous radiation with desorption gases might cause some spurious, transient electrical conditions if the alloy is used for electrical applications.

TABLE 6.1

Source	(Ref. 6.2)
Data	Surface Removal by Sputtering in Space
Nitrogen and oxygen	100 Å/year
Radiation belt protons and heavy ions	0.2 Å/year
Solar flare protons	100 Å/year
Solar proton emission	3 Å/year
Cosmic rays	Insignificant
Meteoroids	< 30 Å/year

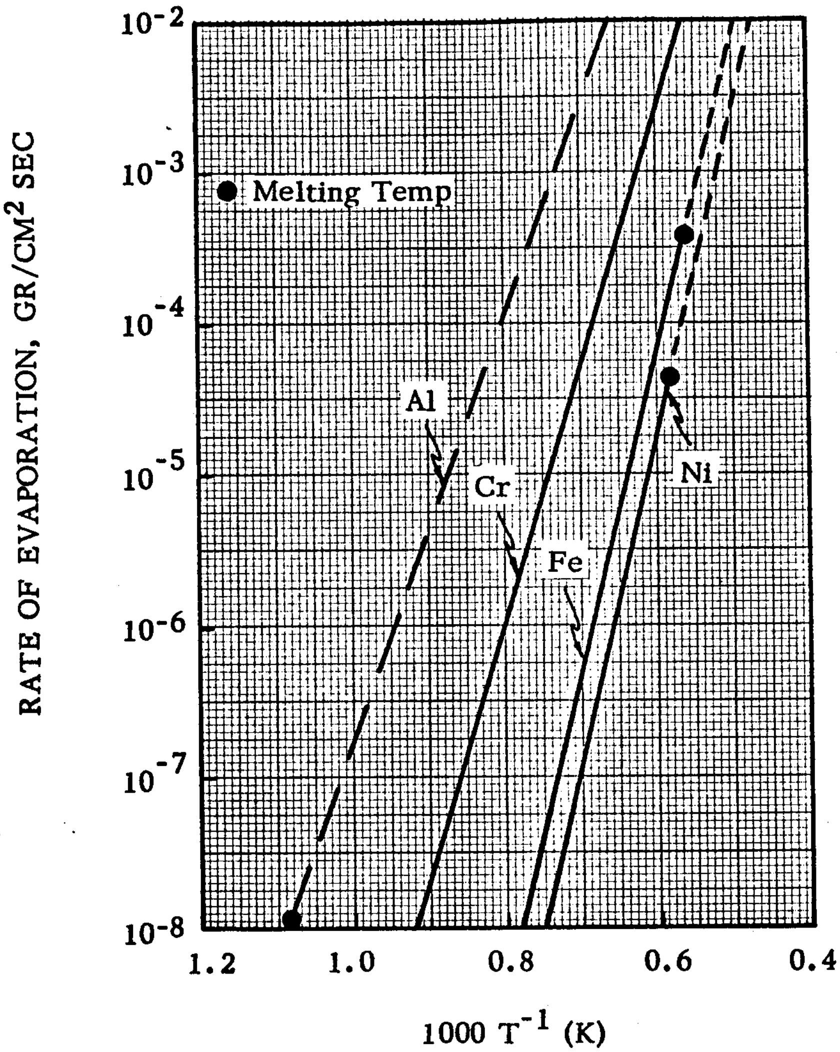

FIG. 6.1 EVAPORATION RATES FOR MAJOR ELEMENTS IN NICKEL-BASE ALLOYS AS COMPARED TO ALUMINUM

(Ref. 6.1)

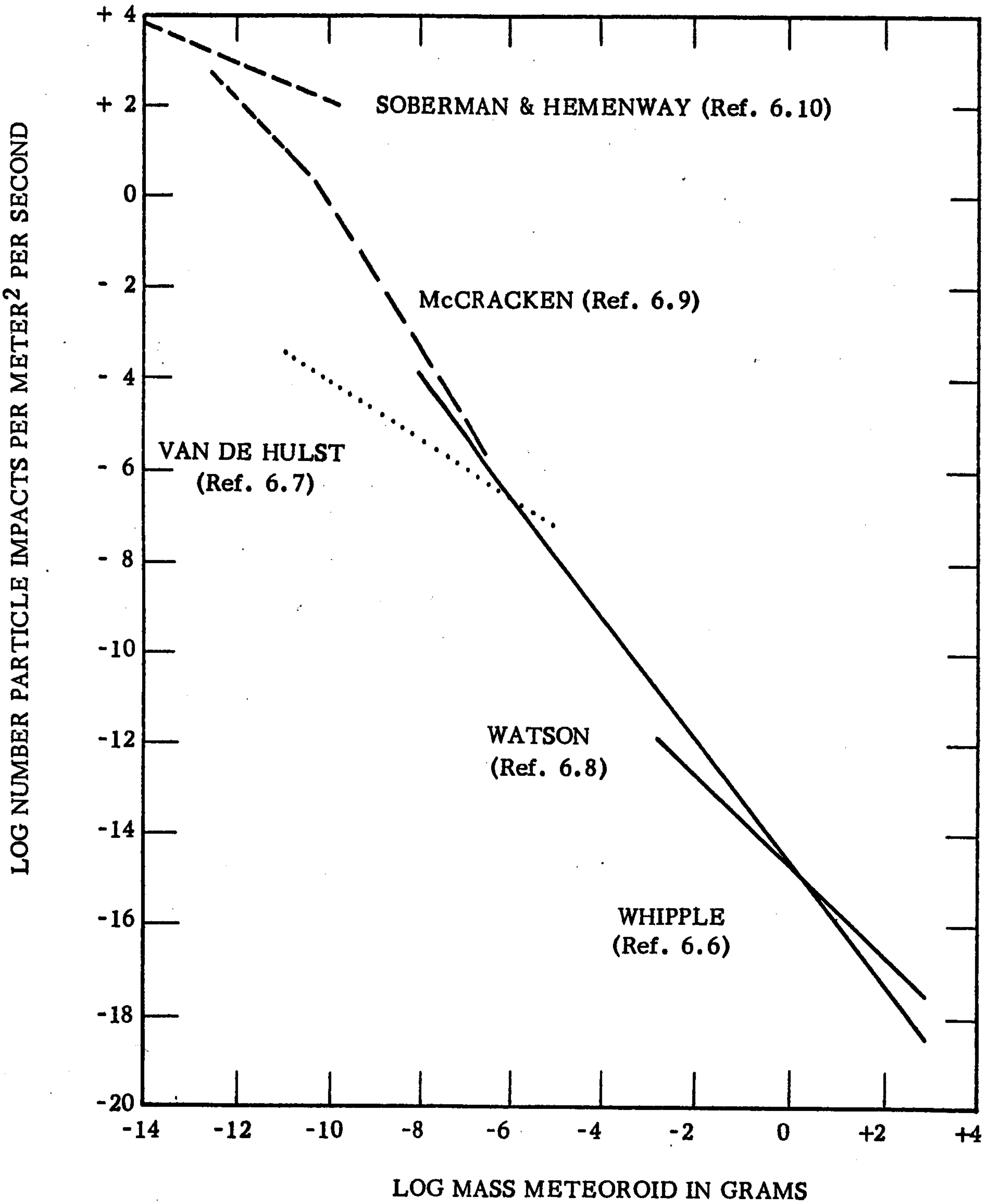

FIG. 6.2 CUMULATIVE METEOROID IMPACT RATES NEAR THE EARTH (Ref. 6.2)

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CHAPTER 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties
7.11 NASA Specified Properties. None.
7.12 AMS Specified Properties, (Ref. 7.1).
7.121 AMS specified properties for annealed sheet, strip and plate, Table 7.121.
7.122 AMS specified properties for aged sheet, strip and plate, Table 7.122.
7.123 AMS specified bend factors for annealed sheet, strip and plate, Table 7.123.
7.13 Military Specified Properties
7.14 Federal Specified Properties
7.15 ASTM Specified Properties

7.2 Elastic Properties and Moduli
7.21 Poisson's ratio at various temperatures, Fig. 7.21.
7.22 Young's modulus of elasticity, E.
7.221 Typical values of E.

RT	29.0×10^3 ksi
1000F	24.8×10^3 ksi
1500F	21.3×10^3 ksi, (Ref. 7.2).

7.222 Typical values of E at various temperatures, Fig. 7.222.
7.23 Compression modulus, E_c.
7.24 Modulus of rigidity (shear modulus), G.
7.241 Typical value of G at various temperatures, Fig. 7.241.
7.25 Tangent modulus
7.26 Secant modulus

7.3 Hardness
7.31 AMS specified hardness for annealed sheet, strip and plate, see Table 7.121.
7.32 AMS specified hardness for aged sheet, strip and plate, see Table 7.122.

7.4 Strength Properties. (See also Section 7.1).
7.41 Tension. (See also Tables 7.121 and 7.122).
7.411 Typical tensile properties
7.4111 Effect of aluminum content on 0.2 percent yield strength and elongation of hot rolled bar, Fig. 7.4111.
7.4112 Effect of age hardening on yield strength, Fig. 7.4112.
7.4113 Effect of final aging temperature on room temperature properties of sheet, Fig. 7.4113.
7.4114 Typical tensile and impact properties for annealed and aged pancake forgings, Table 7.4114.

7.4115 Effect of annealing temperature on room temperature tensile properties, Fig. 7.4115.

7.4116 Effect of cold work on room temperature tensile properties of sheet and strip, Fig. 7.4116.

7.412 Stress-strain diagrams (tension)

7.4121 Typical stress-strain curve at room temperature for single aged sheet, Fig. 7.4121.

7.413 Effect of low temperature on tensile properties.

7.4131 Effect of low temperatures on tensile properties of aged sheet, Fig. 7.4131.

7.4132 Effect of low temperatures on F_{tu} of cold reduced and aged sheet, Fig. 7.4132.

7.4133 Effect of low temperatures on F_{ty} and elongation of cold reduced and aged sheet, Fig. 7.4133.

7.414 Effect of elevated temperatures on tensile properties.

7.4141 Effect of test temperature on tensile properties of sheet, Fig. 7.4141.

7.4142 Effect of test temperature on tensile properties of cold rolled and aged sheet, Fig. 7.4142.

7.4143 Effect of room and elevated temperature on tensile properties of wrought sheet and bar, Fig. 7.4143.

7.4144 Effect of test temperature on tensile properties of hot rolled bar, Fig. 7.4144.

7.4145 Tensile properties of forgings at various temperatures for three different heat treatments, Fig. 7.4145.

7.4146 Effect of test temperature on tensile properties of investment castings, Fig. 7.4146.

7.4147 Effect of room and elevated temperatures on tensile properties of cast test bars, Fig. 7.4147.

7.42 Compression

7.43 Bending

7.44 Shear and torsion

7.45 Bearing

7.46 Fracture

7.461 Notch properties

7.4611 Notch strength of aged sheet at low temperatures, Fig. 7.4611.

7.4612 Notch strength of cold reduced and aged sheet at low temperatures, Fig. 7.4612.

7.4613 Net section strength of center notch fatigue cracked specimens compared to round notch fatigue cracked specimens, Fig. 7.4613.

7.4614 Sharp notch data for sheet at elevated temperatures, Fig. 7.4614.

7.462 Fracture toughness

7.4621 Net section strength and fracture toughness of aged forgings, Fig. 7.4621.

AMS SPECIFIED PROPERTIES
FOR ANNEALED SHEET, STRIP AND PLATE

TABLE 7.121

Alloy	Inconel Alloy 718	
Specification	AMS 5596 A	
Property	Tensile and Hardness (a)	
Form	Sheet, Strip and Plate (d)	
Condition	Annealed (b)	
Test Temp, F	RT	
Thickness, in	≤ 0.187	> 0.187
F_{tu}, - min-ksi	140.0	150.0
F_{ty}, -min-ksi (c)	80.0	90.0
e(2in or 4D), -min, percent	30	40
Hardness, -max		
Rockwell B Scale	100	-
Rockwell C Scale	-	25

(a) For widths 9 inches and over, tensile test specimens are taken perpendicular to direction of rolling. For widths less than 9 inches, specimens are taken parallel to direction of rolling.

(b) Annealed 1725-1775F (in a suitable protective atmosphere), hold 30 minues maximum, air cool or faster.

(c) Yield strength at 0.2% offset or at extension of 0.0094 inch (in 2 inches) for thicknesses up to 0.187 inch and 0.010 inch (in 2 inches) for thicknesses greater than 0.187 inch. (E = 29,600 ksi).

(d) Material shall be consumable electrode or vacuum induction melted.

AMS SPECIFIED PROPERTIES FOR AGED SHEET, STRIP AND PLATE

TABLE 7.122

Alloy	Inconel Alloy 718		
Specification	AMS 5596A		
Property	Tensile (a)		
Form	Sheet, Strip and Plate (c)		
Condition	Anneal plus Age (b)		
Test Temp, F	RT	1200F	
Thickness, in	Not Given	≤ 0.015	> 0.015
F_{tu}, - min-ksi	180.0	140.0	145.0
F_{ty}, - min-ksi (d)	150.0	115.0	120.0
e(2in or 4D) - min-percent	15	10	10
Hardness, - min Rockwell C Scale	36	-	-

(a) For widths 9 inches and over, tensile specimens are taken perpendicular to direction of rolling. For widths less than 9 inches, specimens are taken parallel to direction of rolling.

(b) Annealed 1725-1775F (in suitable protective atmosphere); hold 1 hour, air cool or faster.
Age 1310-1340F, hold 8 hours, furnace cool at rate of 85-115F per hour to 1135F-1165F, hold 8 hours, air cool.
Alternate procedure: Age 1310-1340F, hold 3 hours, furnace cool to 1135-1165F, hold until total aging time of 18 hours is reached, air cool.

(c) Material shall be consumable electrode or vacuum induction melted.

(d) Yield strength at 0.2% offset or at extension of 0.014 inch (in 2 inches) at room temperature (E = 29,600 ksi). At 1200F extension of 0.0133 inch (in 2 inches) for material up to 0.015 inch, and extension of 0.0138 for material thicker than 0.015 inch.

AMS SPECIFIED BEND FACTORS
FOR ANNEALED SHEET, STRIP AND PLATE

TABLE 7.123

Alloy	Inconel Alloy 718	
Property	Bend Factor (a)	
Form	Sheet, Strip and Plate (b)	
Specification	AMS 5596A	
Condition	Annealed (c)	
Thickness, in	≤ 0.050	0.050 to 0.188
Bend Factor	1t	2t

(a) Material shall withstand, without cracking, bending through an angle of 180 degrees around a diameter equal to bend factor times nominal thickness (t) with axis of bend parallel to direction of rolling.

(b) Material shall be consumable-electrode or vacuum induction melted.

(c) Annealed 1725-1775F (in suitable protective atmosphere), hold 30 minutes maximum, air cool or faster.

TYPICAL TENSILE AND IMPACT PROPERTIES FOR ANNEALED AND AGED PANCAKE FORGINGS

TABLE 7.4114

Source		(Ref. 7.8)				
Alloy		Inconel Alloy 718				
Form		Pancake Forgings				
Condition		Ann + Age				
Thickness, in		8 in dia				
Test Orientation		Radial Center Top Edge	Radial Center Center	Radial Center Bottom Edge	Tangential Top Edge	Tangential Bottom Edge
F_{tu}, -ksi	(a)	180	188	177	193	196
	(b)	182	196	186.5	209	210
F_{ty}, -ksi	(a)	146.5	147.5	145.5	156	160
	(b)	159	160	159.5	181	179
e, (2in) -percent	(a)	20	24	14	21	20
	(b)	10	24	16	19	18
RA, -percent	(a)	22	34	16	32	36
	(b)	10.5	33	19	27.5	29.5
Impact-ft-lb	(a)	28	22-25	28	17-22	21-23
	(b)	-	-	-	17-21	21-21

(a) 1800F, 1 hr + 1325F, 8 hr, FC 100F/hr to 1150F, + 1150F, 8 hr.
(b) 1800F, 1 hr + 1325F, 16 hr

Strain rate 0.005 in/in/minute through 0.2% yield strength, then 0.050 in/in/minute.

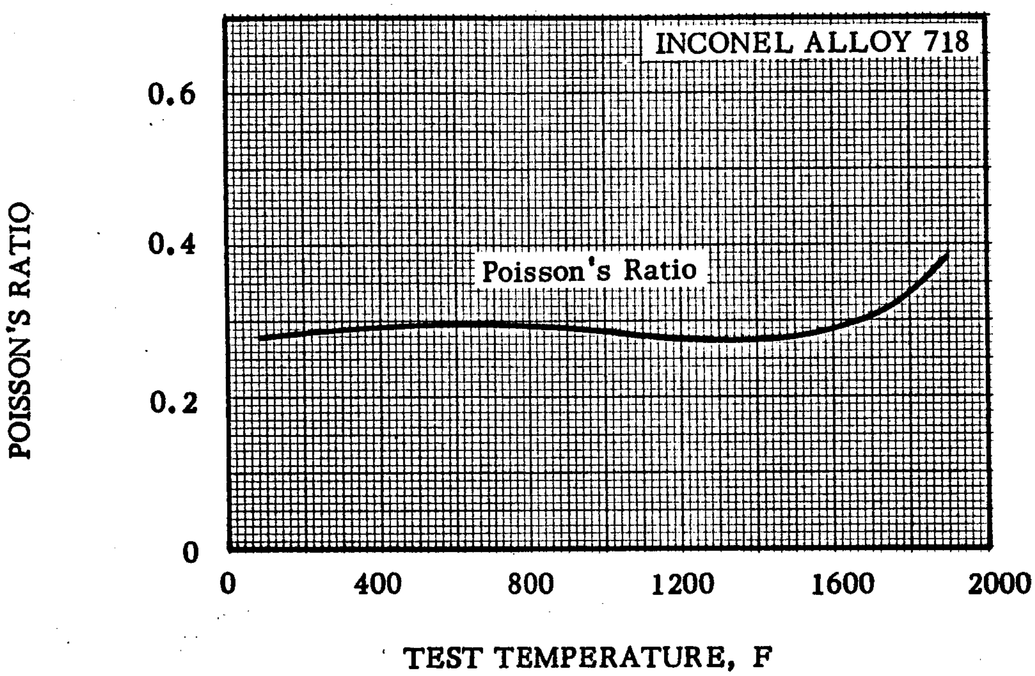

FIG. 7.21 POISSON'S RATIO AT VARIOUS TEMPERATURES (Ref. 7.6)

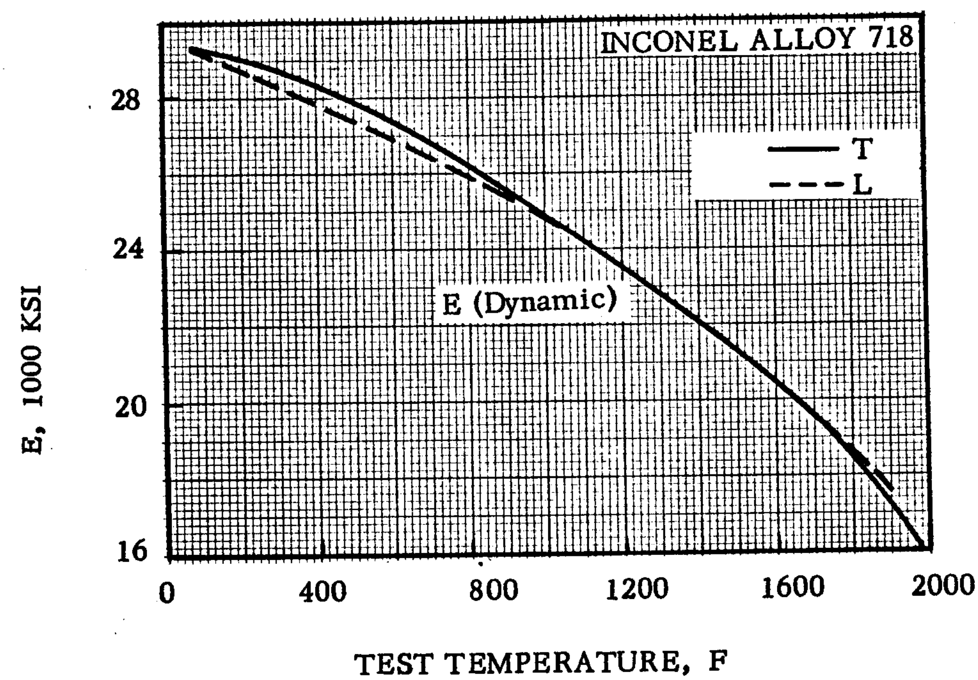

FIG. 7.222 TYPICAL VALUES OF E AT VARIOUS TEMPERATURES (Ref. 7.6)

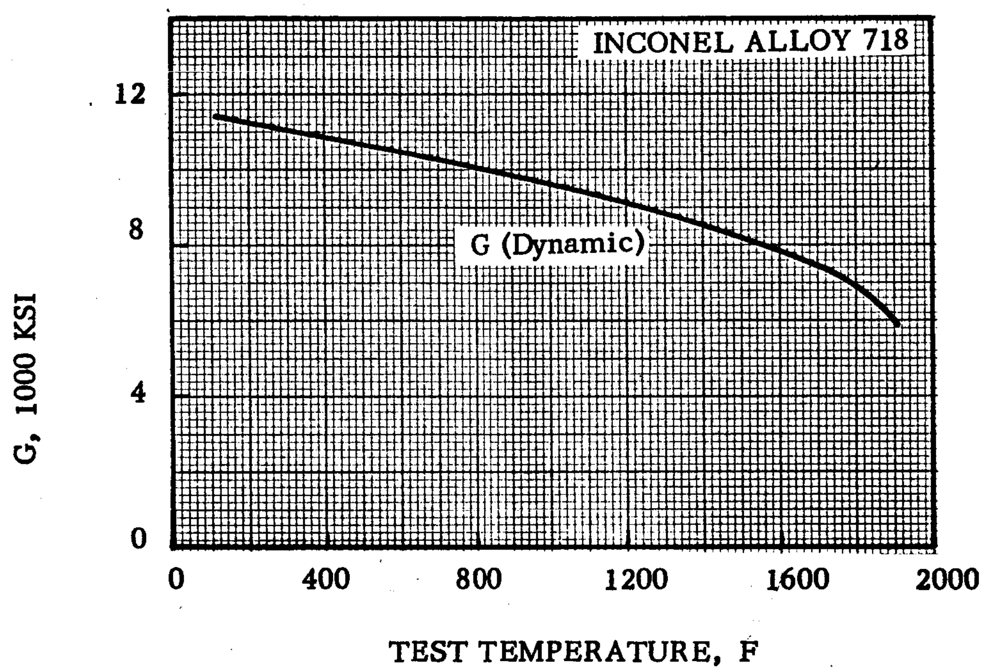

FIG. 7.241 TYPICAL VALUE OF G AT VARIOUS TEMPERATURES (Ref. 7.6)

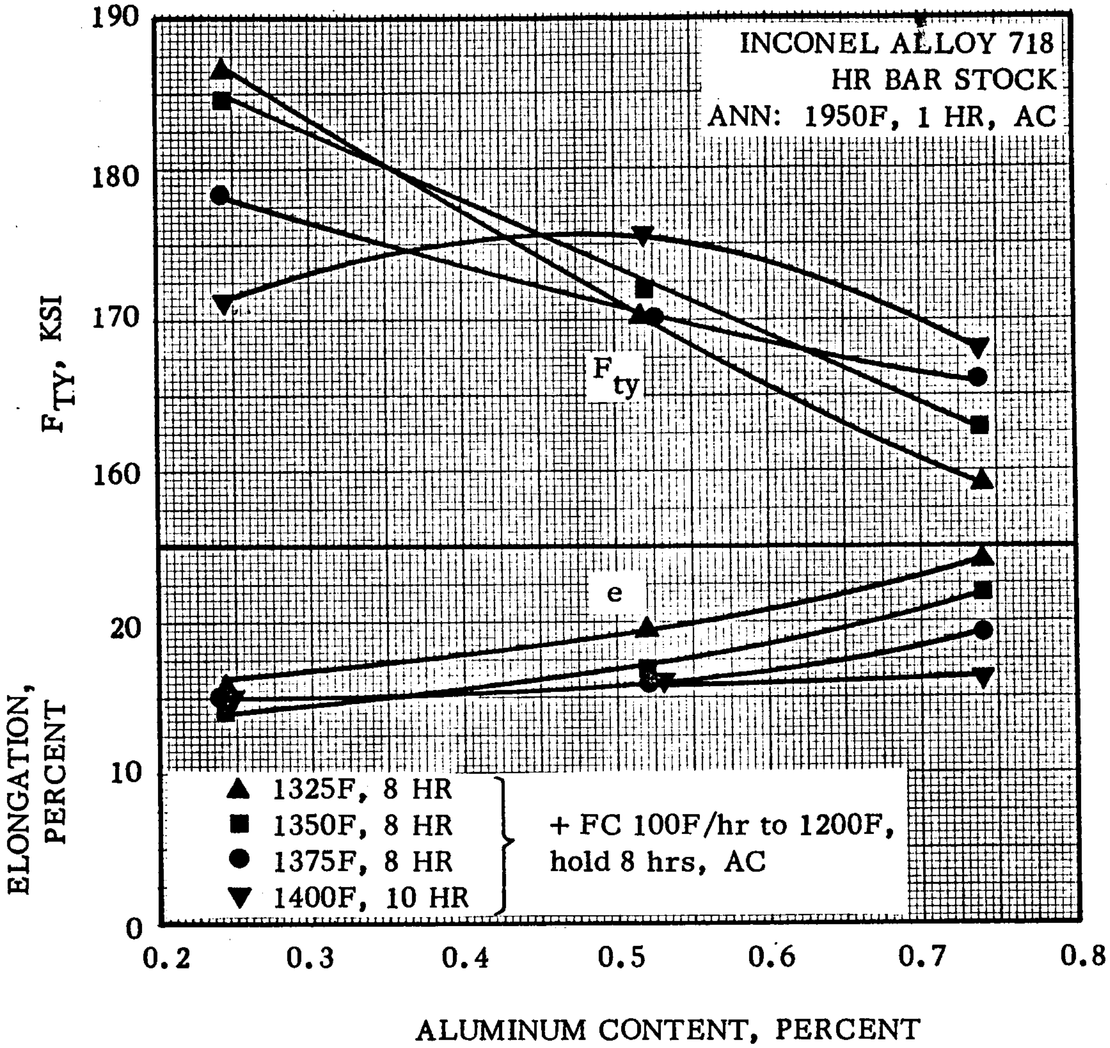

FIG. 7.4111 EFFECT OF ALUMINUM CONTENT ON 0.2 PERCENT YIELD STRENGTH AND ELONGATION OF HOT ROLLED BAR

(Ref. 7.7)

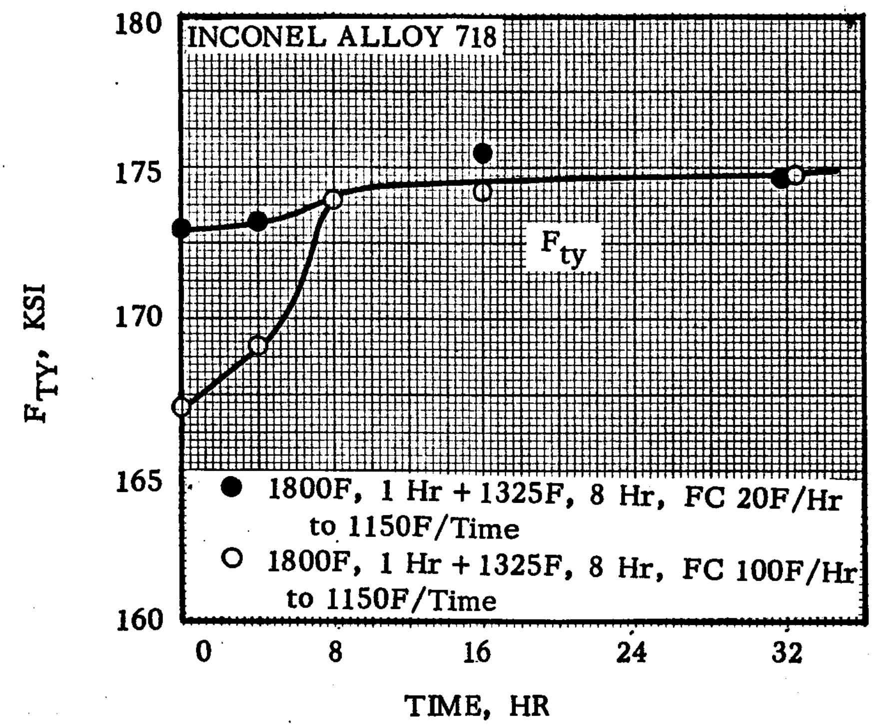

FIG. 7.4112 EFFECT OF AGE HARDENING ON YIELD STRENGTH OF ALLOY

(Ref. 7.8)

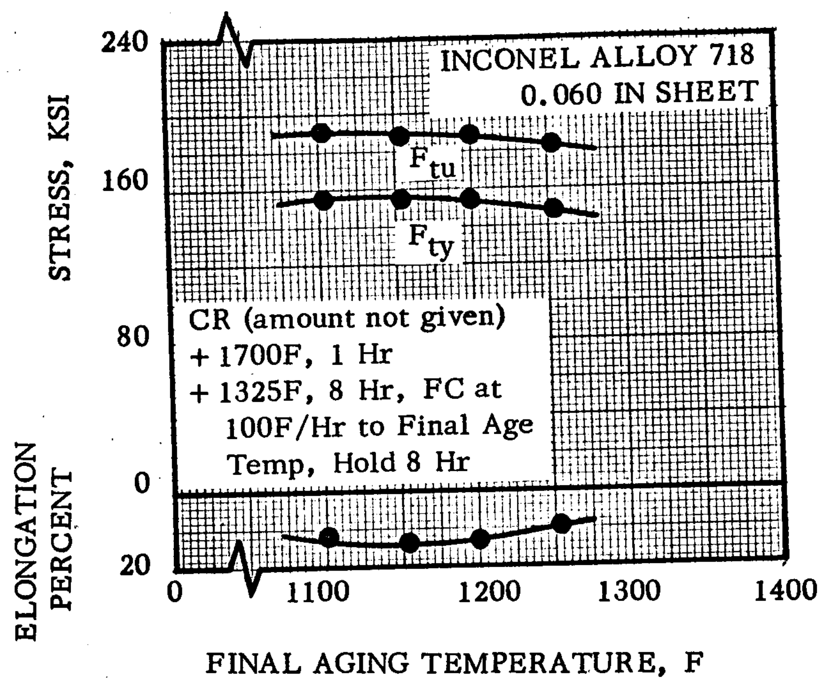

FIG. 7.4113 EFFECT OF FINAL AGE TEMPERATURE ON ROOM TEMPERATURE PROPERTIES OF SHEET

(Ref. 7.8)

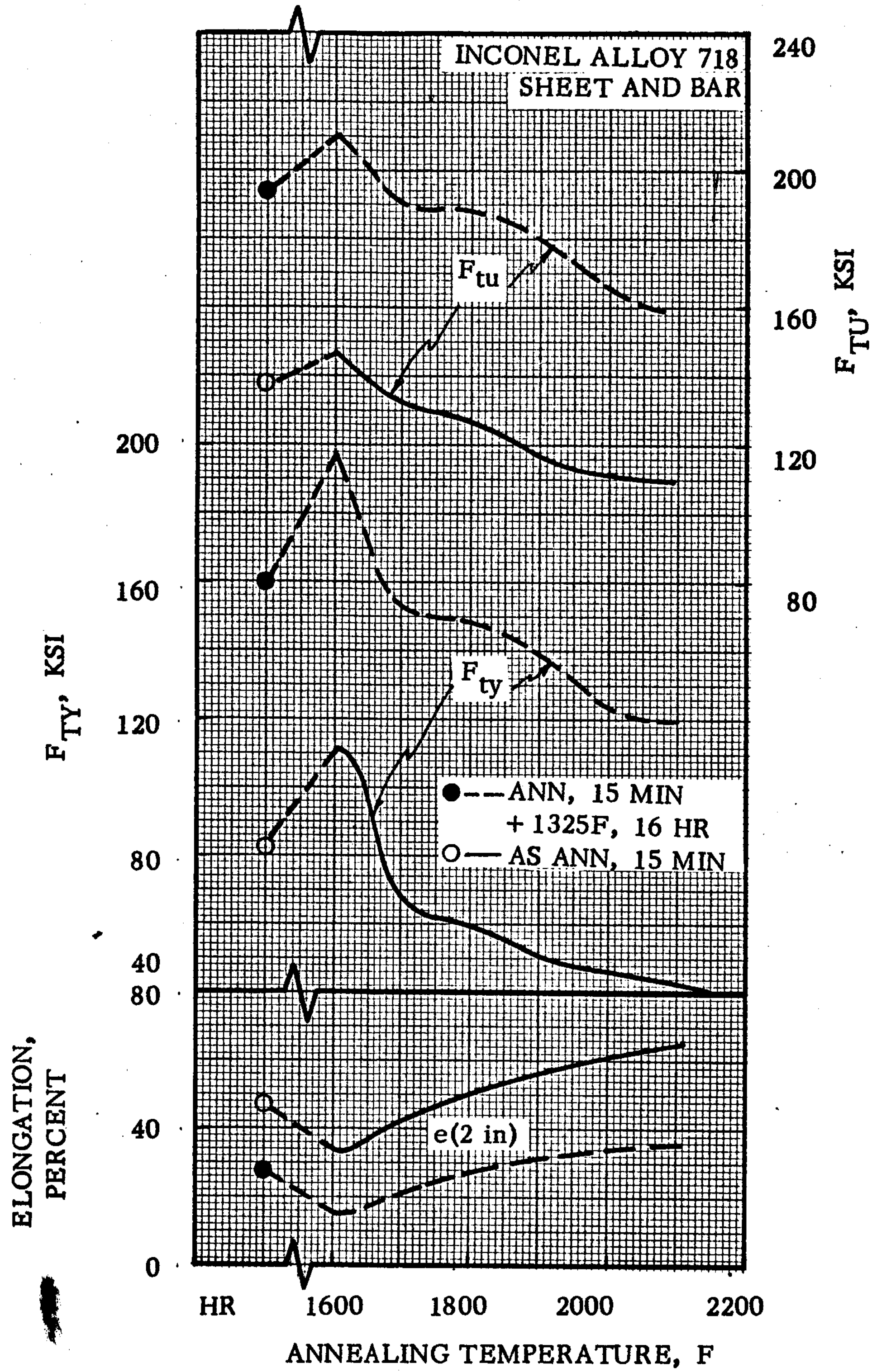

FIG. 7.4115 EFFECT OF ANNEALING TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES (Ref. 7.3)

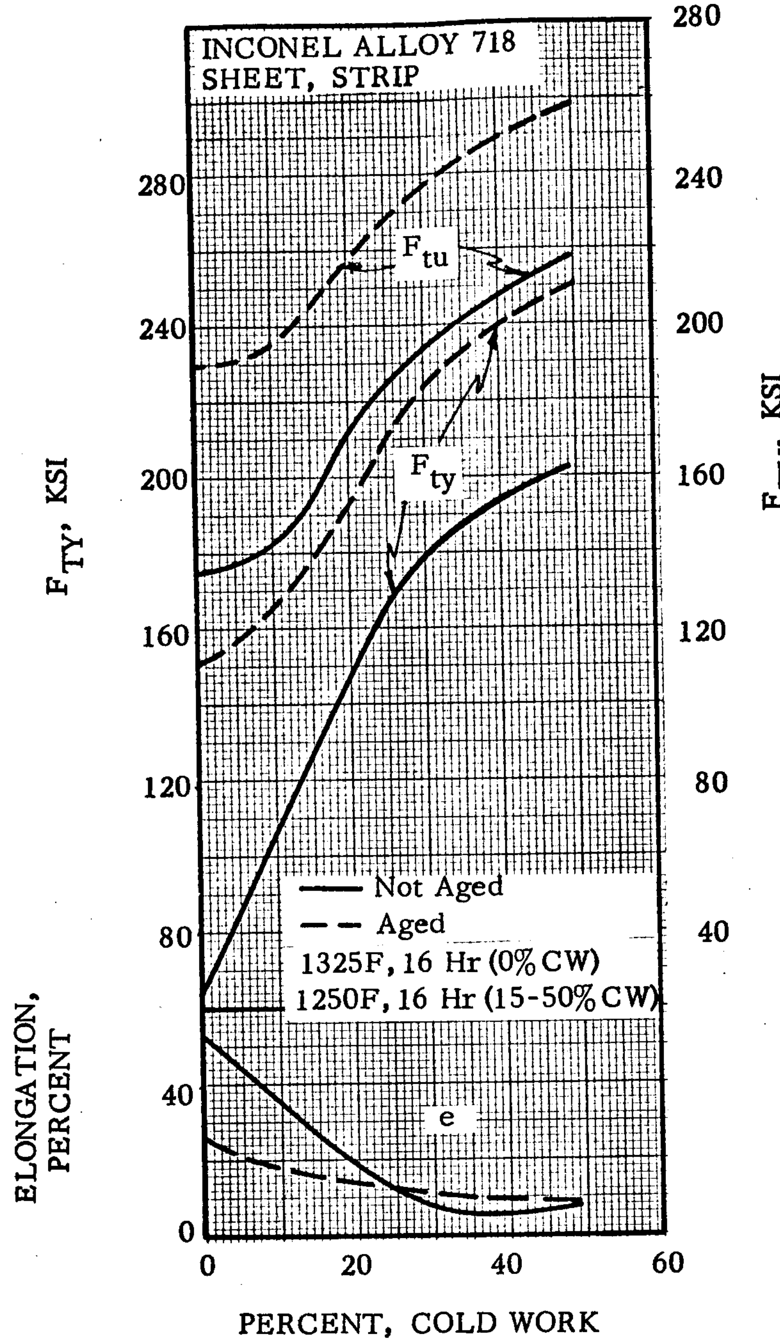

FIG. 7.4116 EFFECT OF COLD WORK ON ROOM TEMPERATURE TENSILE PROPERTIES OF SHEET AND STRIP

(Ref. 7.3)

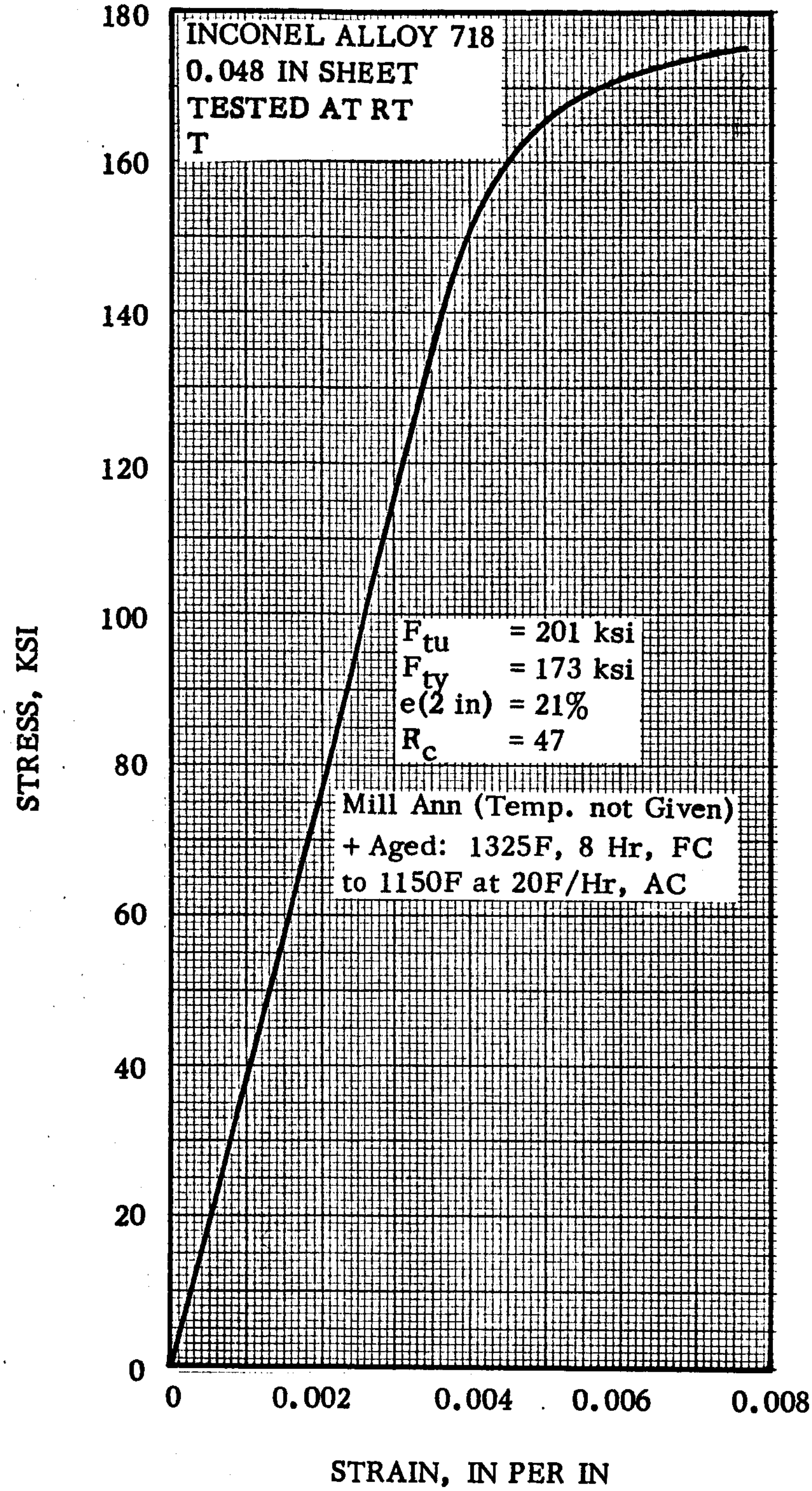

FIG. 7.4121 TYPICAL STRESS-STRAIN CURVE AT ROOM TEMPERATURE FOR SINGLE AGED SHEET (Ref. 7.9)

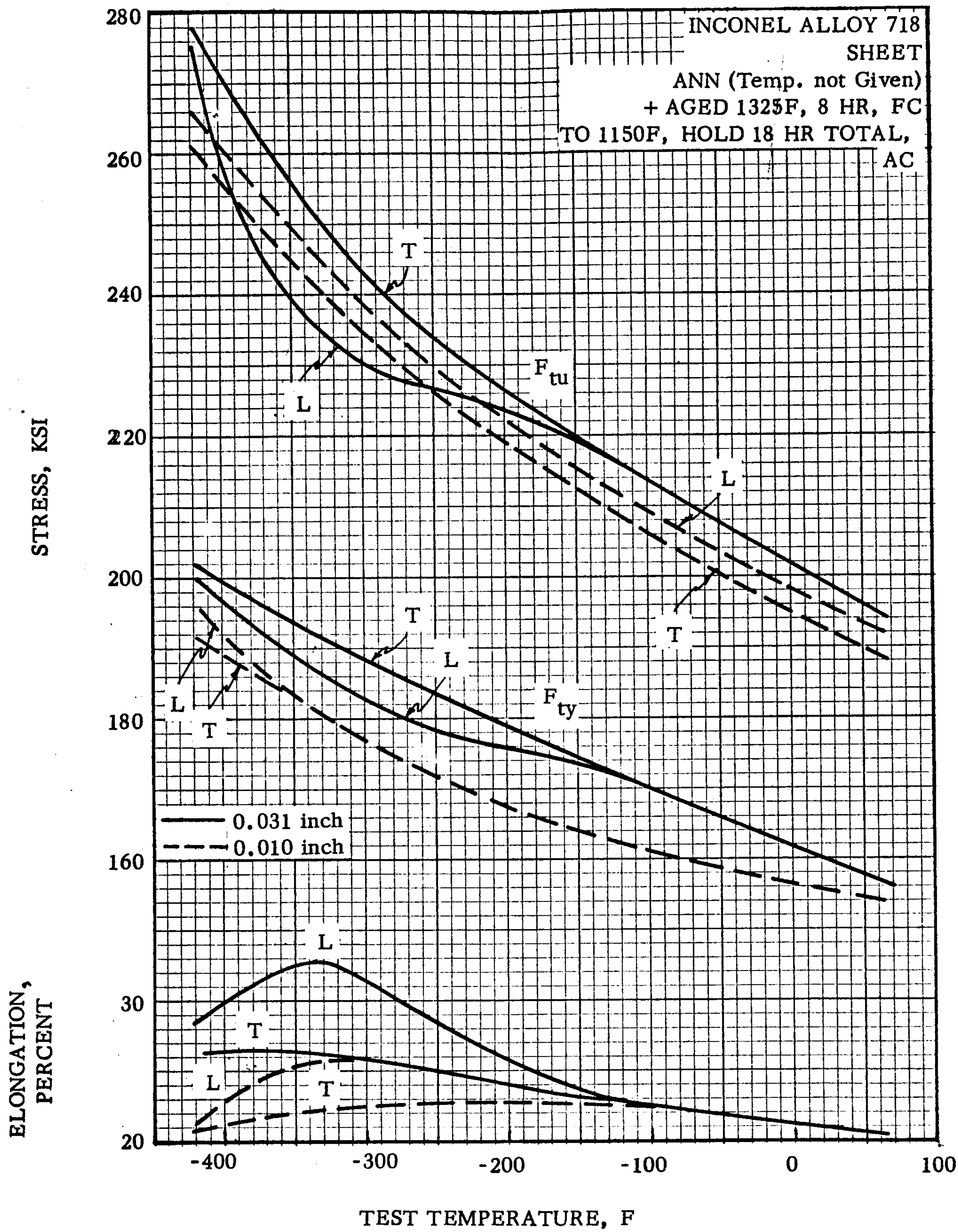

FIG. 7.4131 EFFECT OF LOW TEMPERATURES ON TENSILE PROPERTIES OF AGED SHEET

(Ref. 7.5)

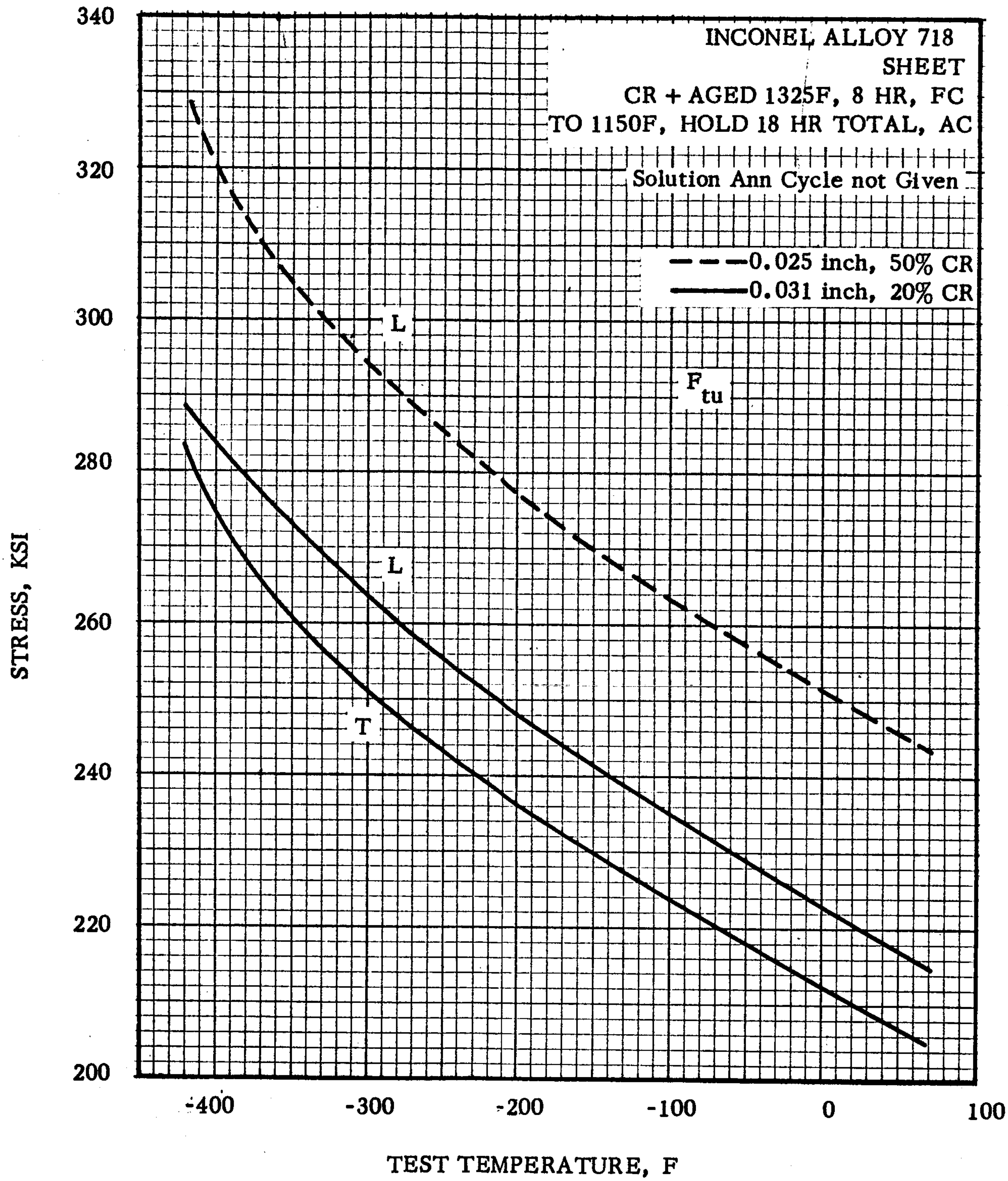

FIG. 7.4132 EFFECT OF LOW TEMPERATURES ON F_{TU} OF COLD REDUCED AND AGED SHEET

(Ref. 7.5)

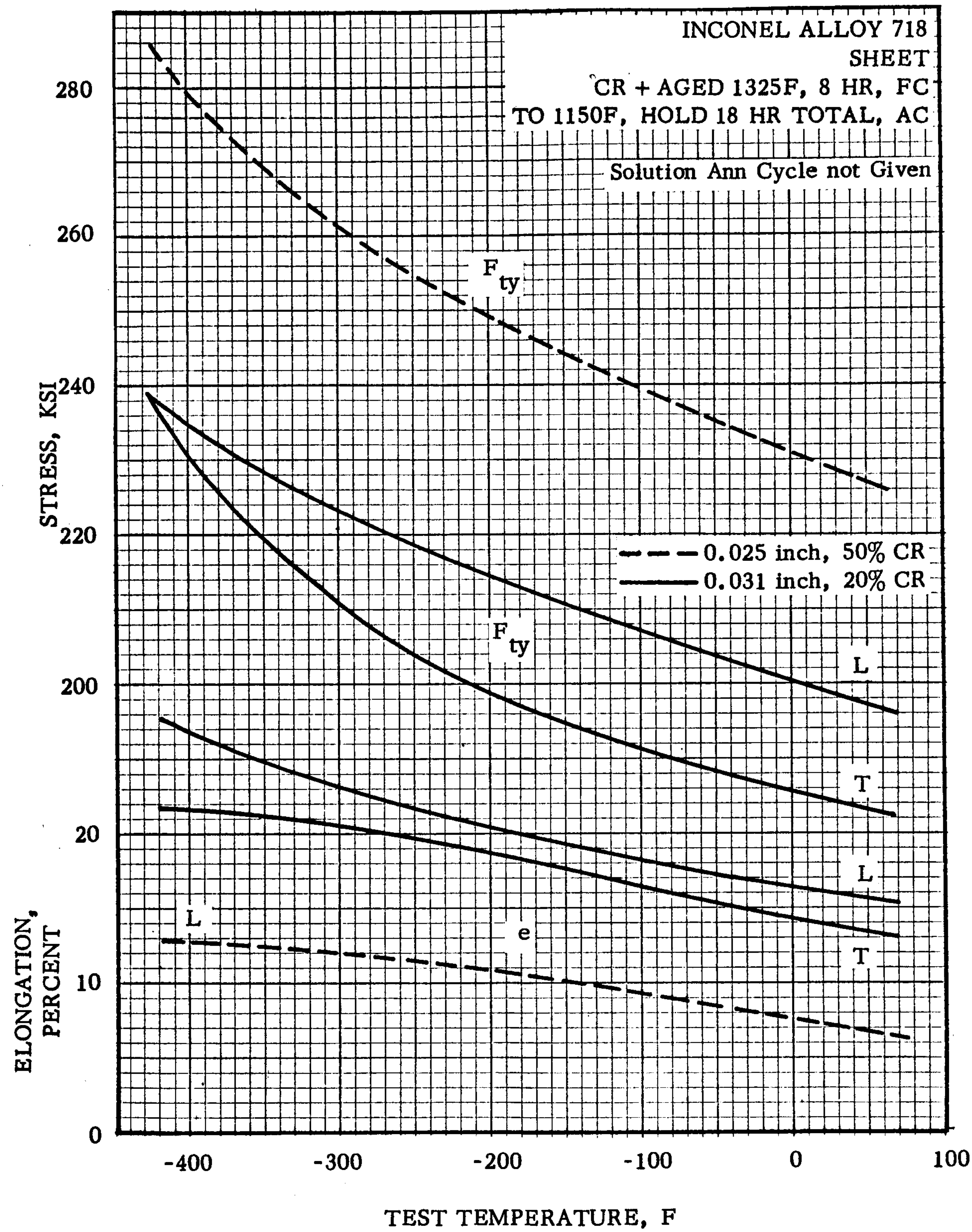

FIG. 7.4133 EFFECT OF LOW TEMPERATURES ON F_{TY} AND ELONGATION OF COLD REDUCED AND AGED SHEET

(Ref. 7.5)

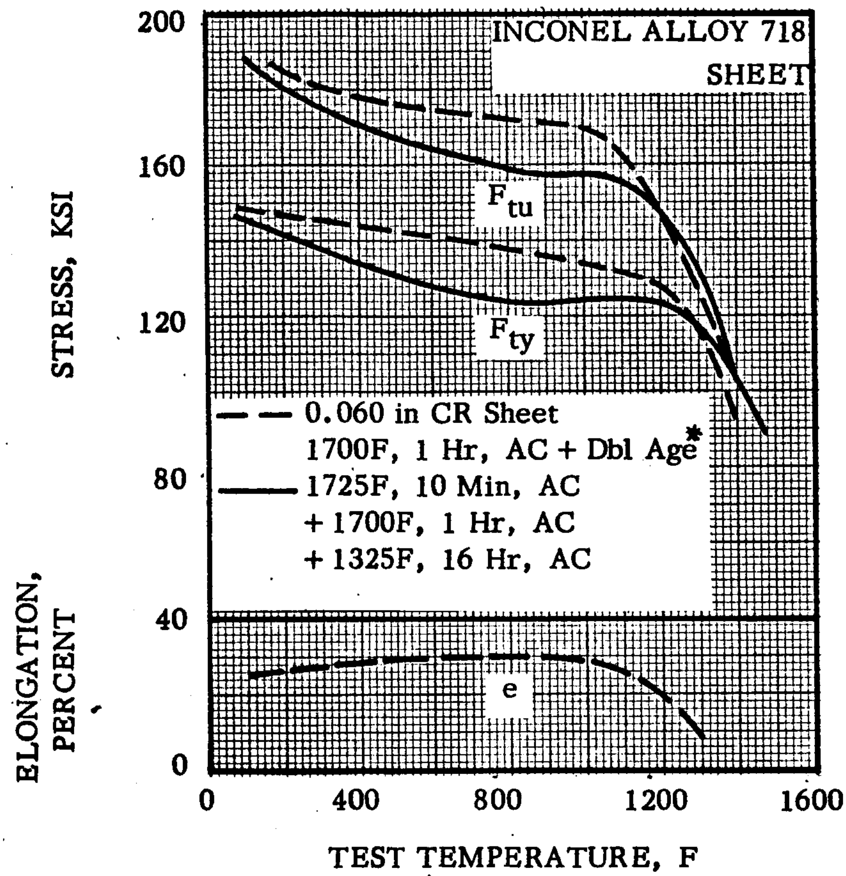

FIG. 7.4141 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF SHEET

(Refs. 7.8 and 7.10)

* 1325F, 8 Hr, FC 100F/Hr to 1150F + 1150F, 8 Hr

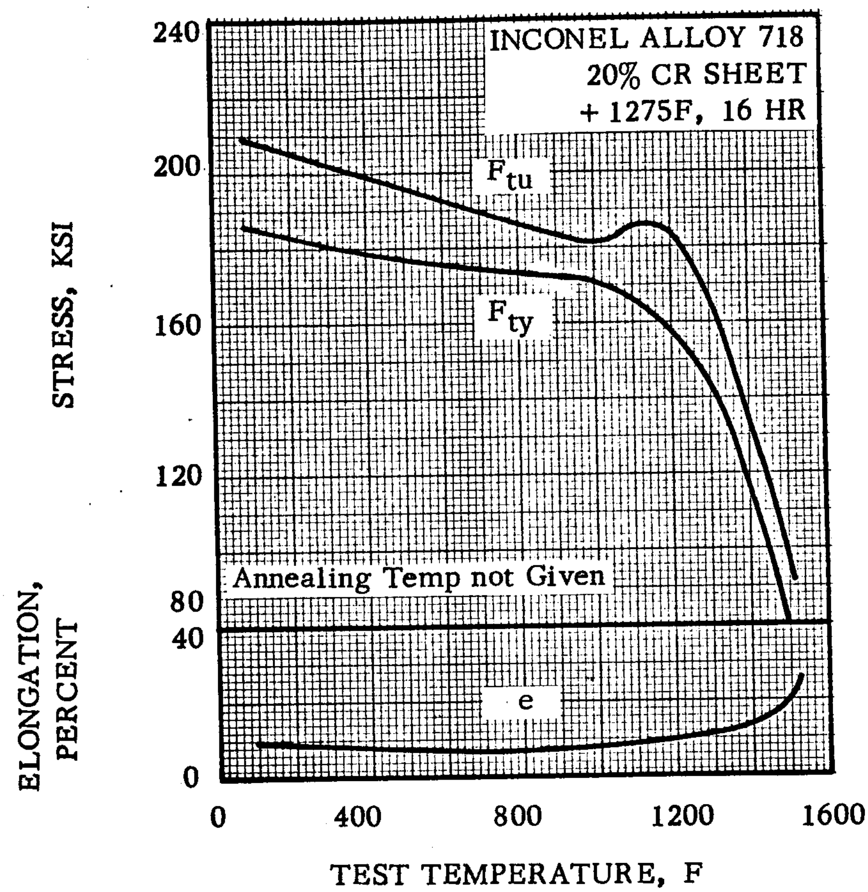

FIG. 7.4142 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF COLD ROLLED AND AGED SHEET

(Ref. 7.3)

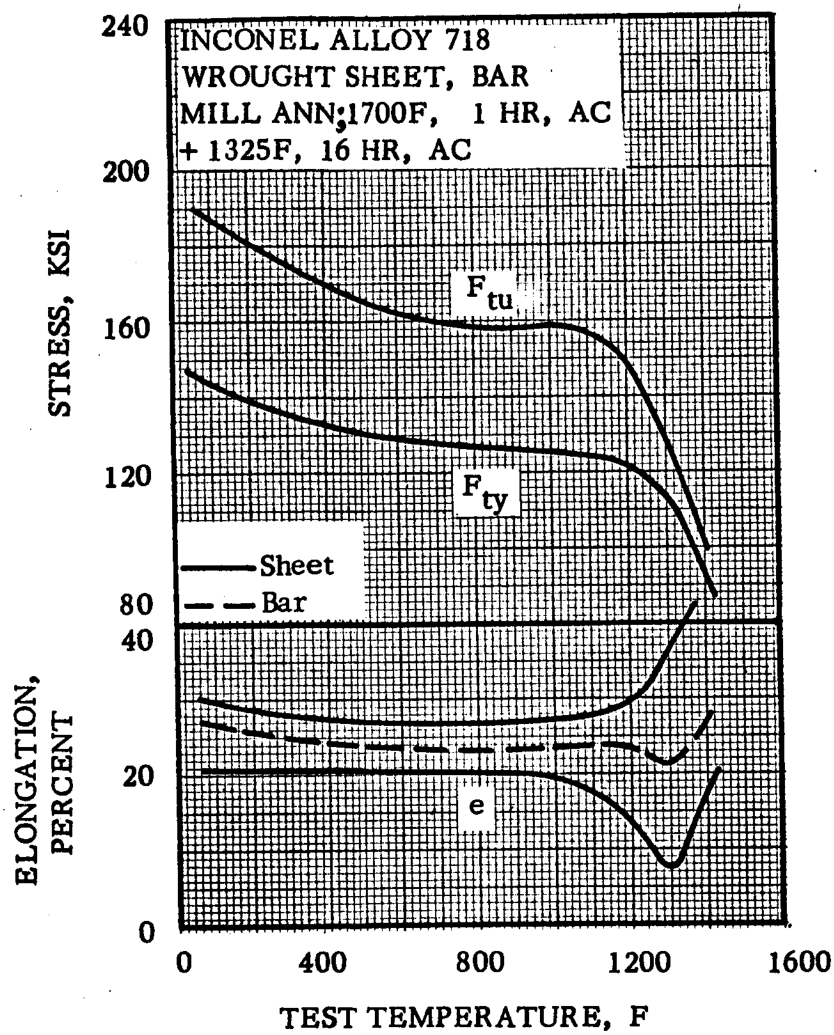

FIG. 7.4143 EFFECT OF ROOM AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF WROUGHT SHEET AND BAR

(Ref. 7.11)

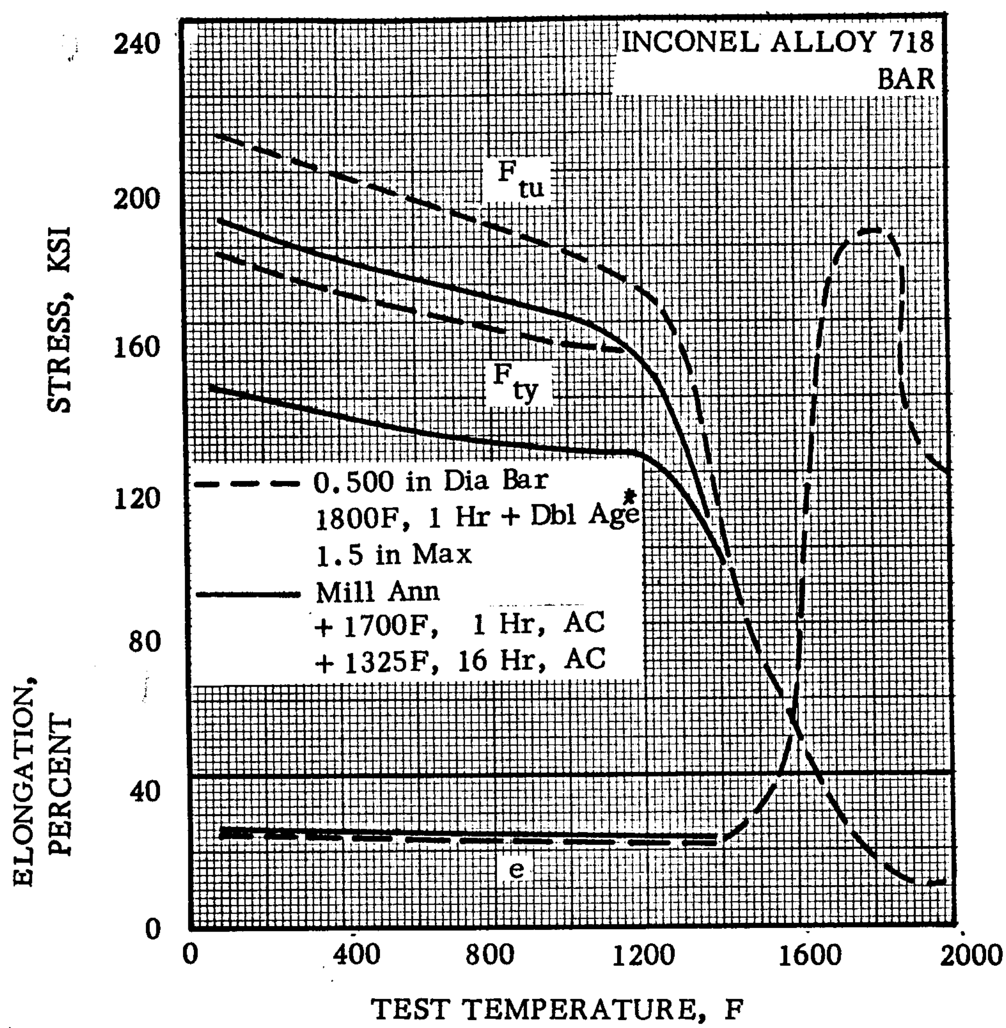

FIG. 7.4144 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF HOT ROLLED BAR (Refs. 7.8 and 7.10)

* 1325F, 8 Hr, FC 100F/Hr to 1150F + 1150F, 8 Hr

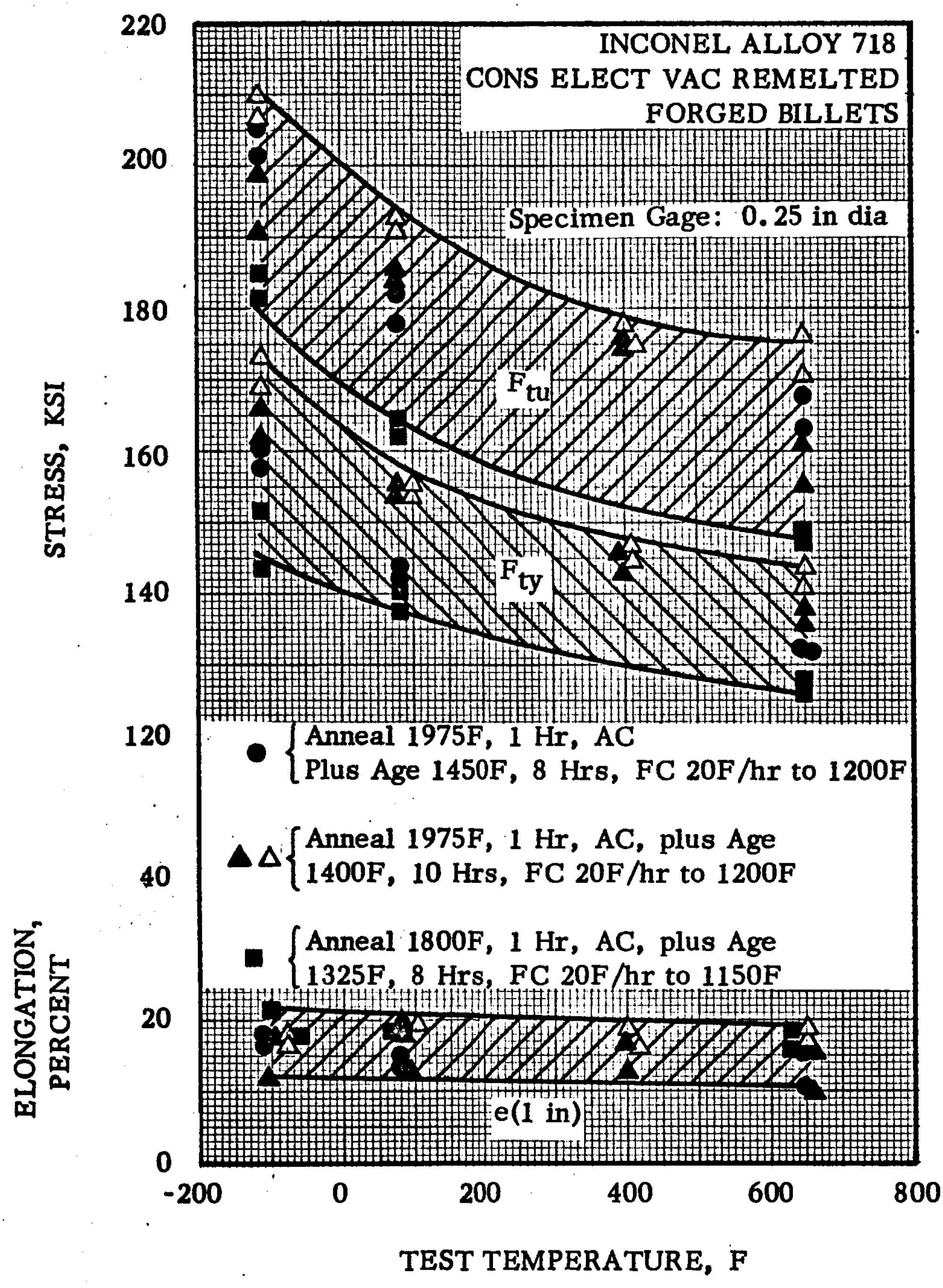

FIG. 7.4145 TENSILE PROPERTIES OF FORGINGS AT VARIOUS TEMPERATURES FOR THREE DIFFERENT HEAT TREATMENTS

(Ref. 7.4)

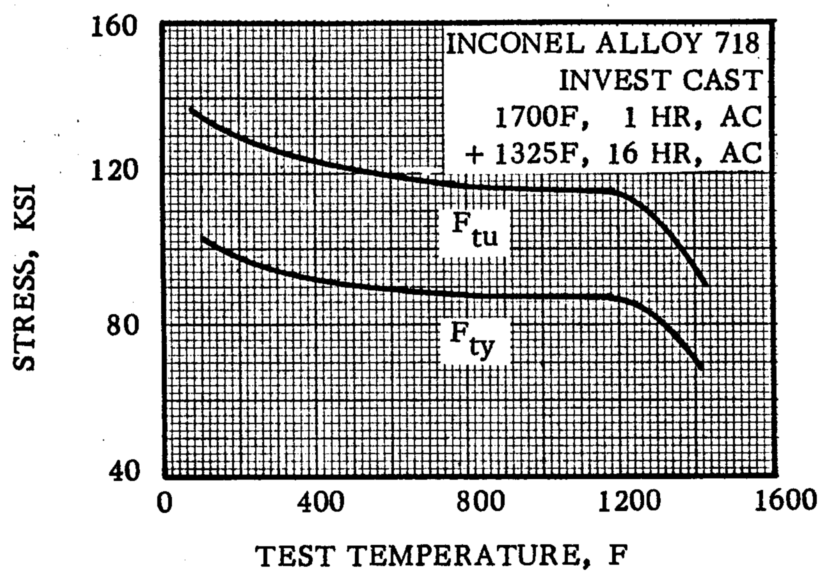

FIG. 7.4146 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF INVESTMENT CASTINGS

(Ref. 7.12)

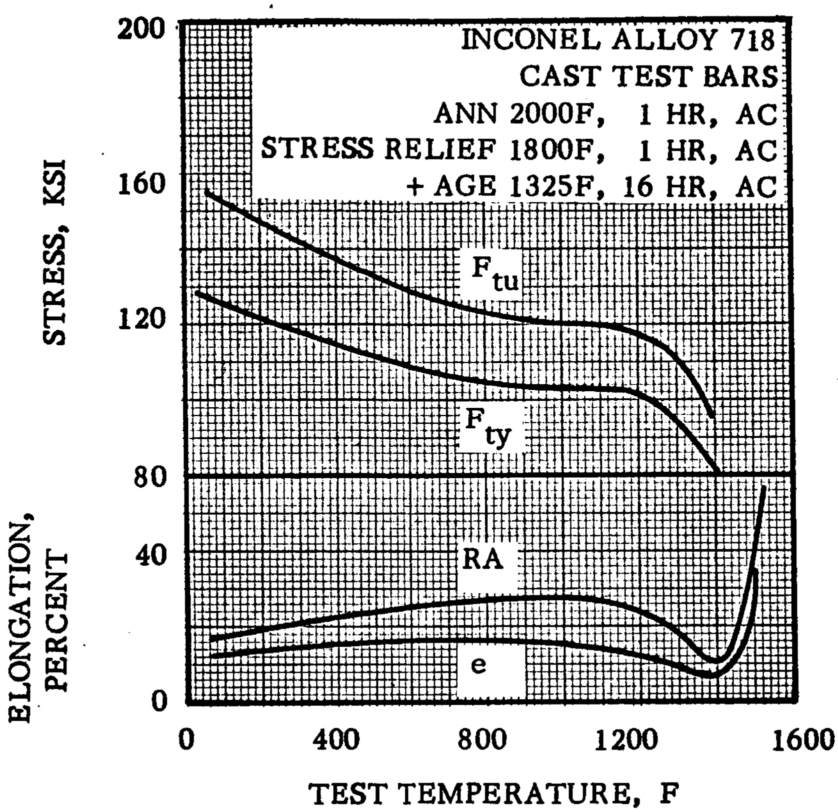

FIG. 7.4147 EFFECT OF ROOM AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF CAST TEST BARS

(Ref. 7.11)

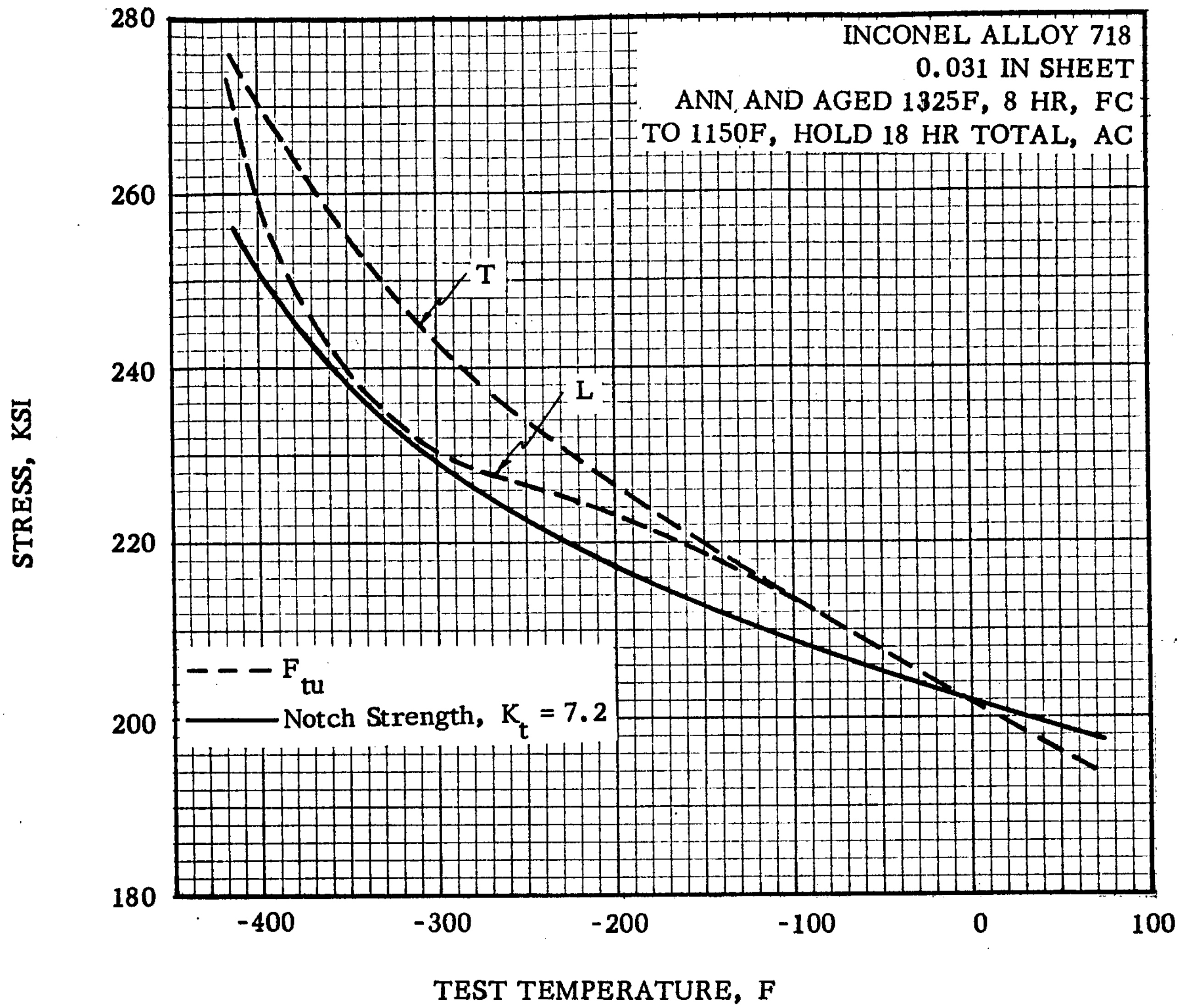

FIG.. 7.4611 NOTCH STRENGTH OF AGED SHEET AT LOW TEMPERATURES (Ref. 7.5)

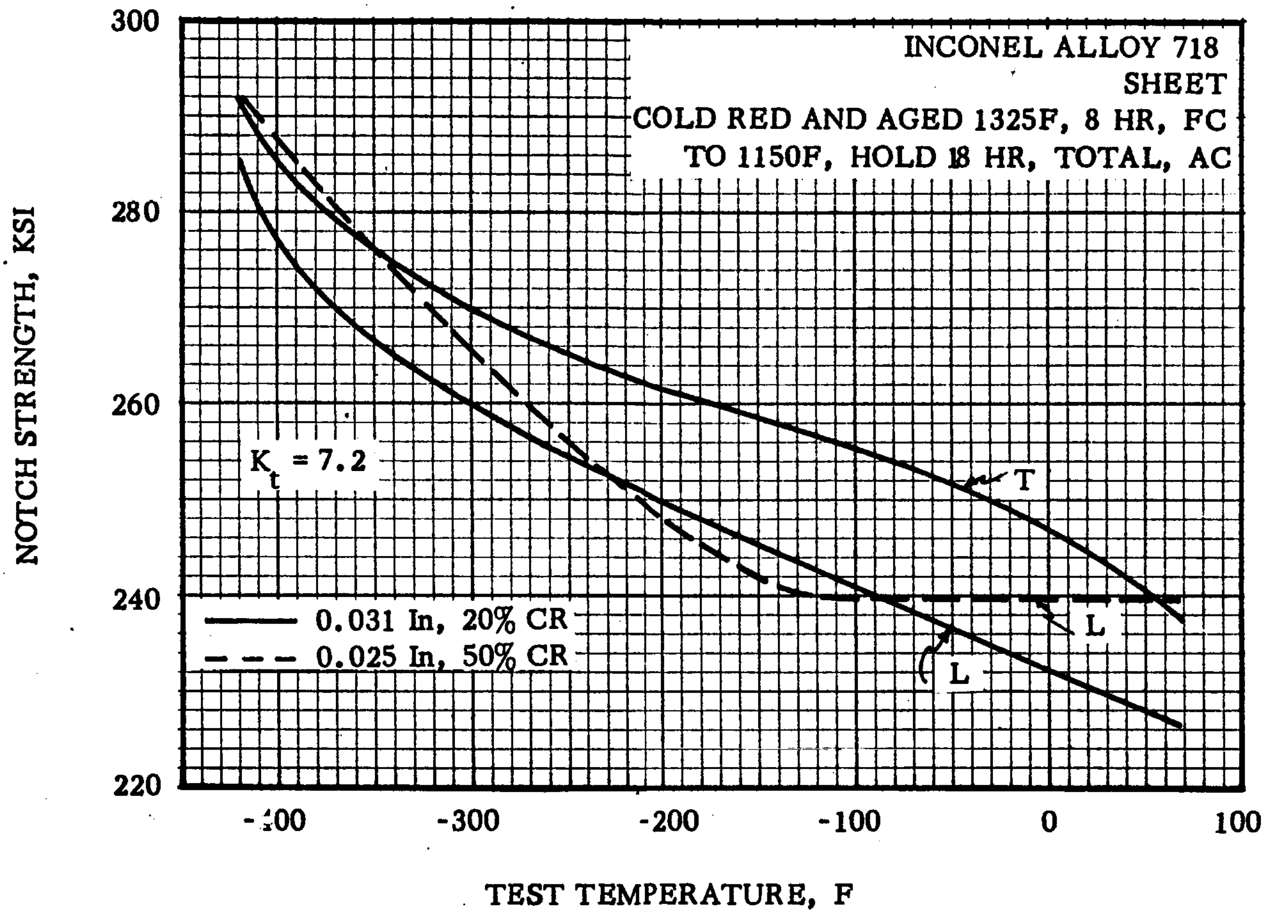

FIG. 7.4612 NOTCH STRENGTH OF COLD REDUCED AND AGED SHEET AT LOW TEMPERATURES

(Ref. 7.5)

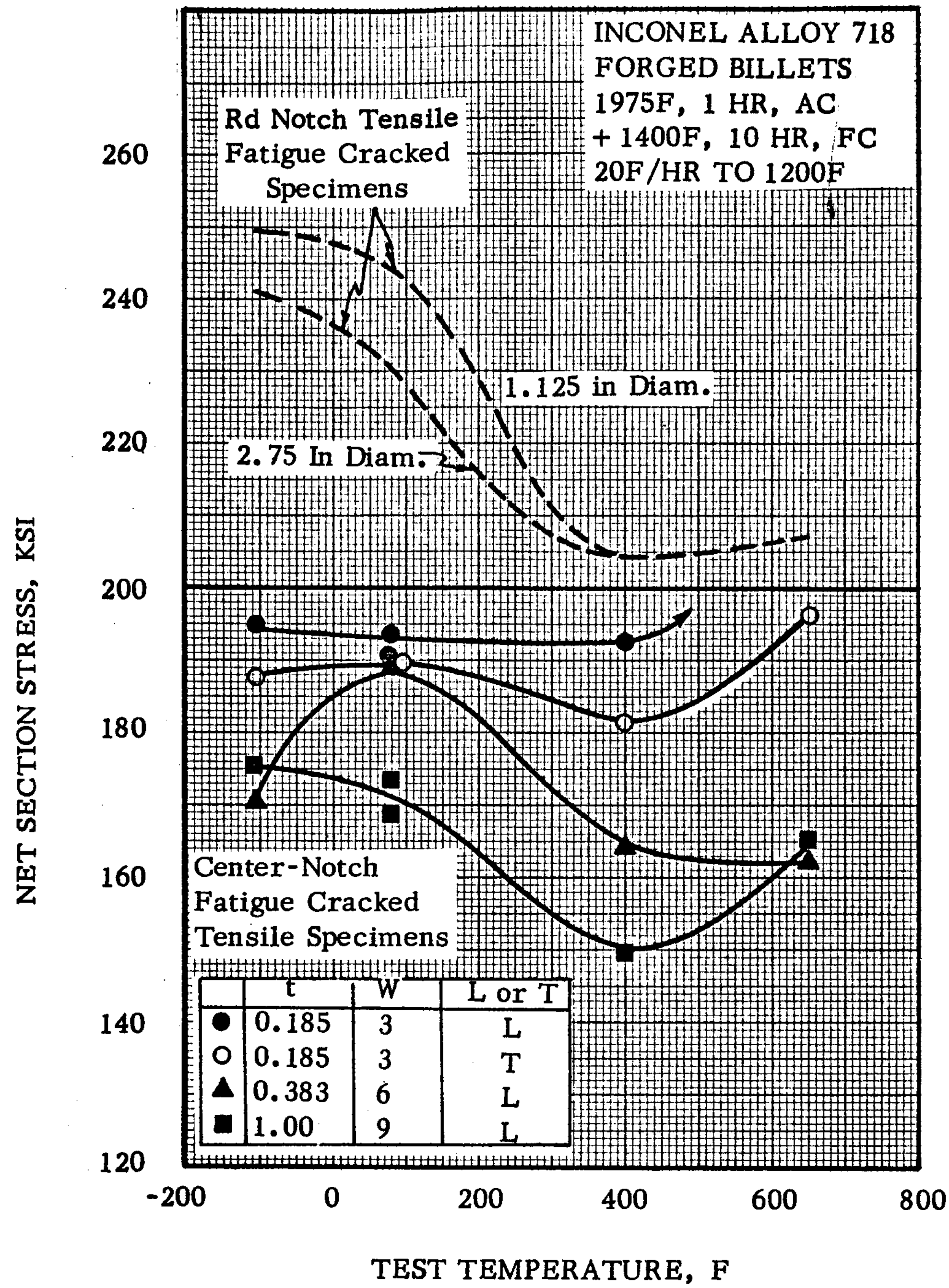

FIG. 7.4613 NET SECTION STRENGTH OF CENTER NOTCH FATIGUE CRACKED SPECIMENS COMPARED TO ROUND NOTCH FATIGUE CRACKED SPECIMENS

(Ref. 7.4)

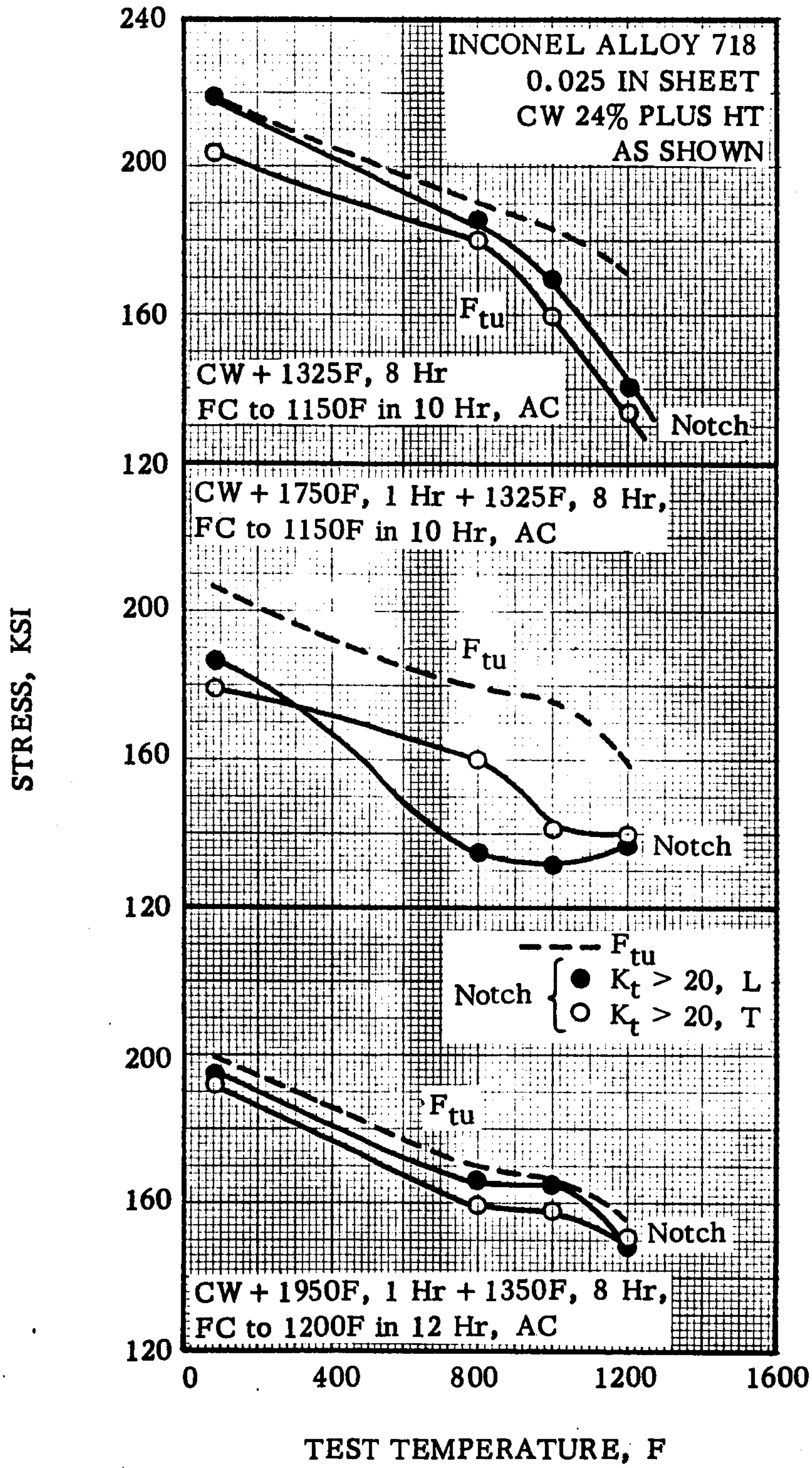

FIG. 7.4614 SHARP NOTCH DATA FOR SHEET AT ELEVATED TEMPERATURES

(Ref. 7.14)

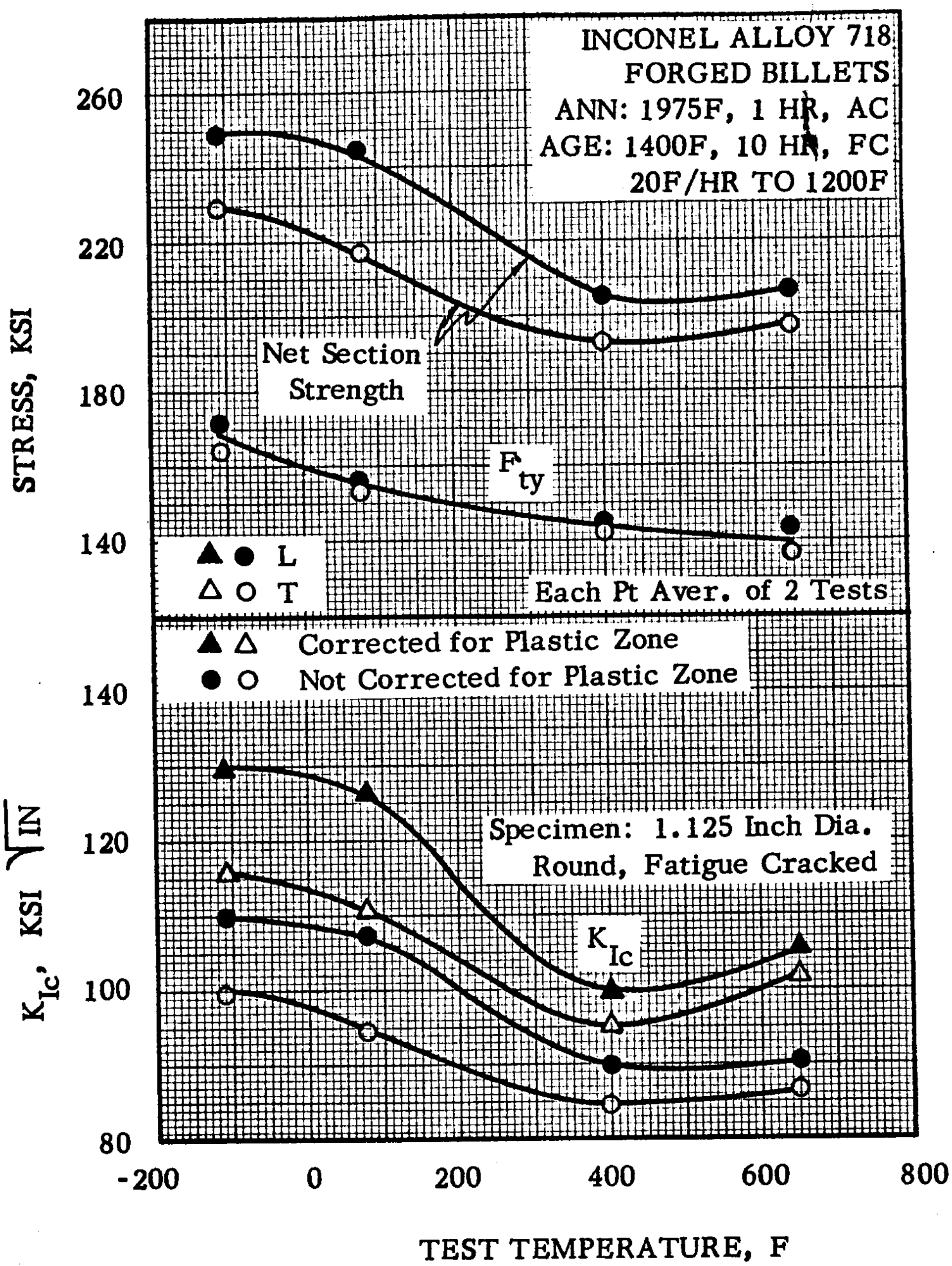

FIG. 7.4621 NET SECTION STRENGTH AND FRACTURE TOUGHNESS OF AGED FORGINGS

(Ref. 7.4)

CHAPTER 7 - REFERENCES

7.1 AMS 5596A, Aerospace Material Specification, Soc. Auto. Eng., Inc., (January 31, 1964; revised June 30, 1964)

7.2 Materials in Design Engineering, Materials Selector Issue, (Mid-October 1965)

7.3 Huntington Alloy Div., International Nickel Co., "Inconel 718, Age-Hardenable, Nickel-Chromium Alloy", (September 1960)

7.4 "Thick Section Fracture Toughness", Boeing-No. American, (Joint Venture), ML-TDR-64-236, (October 1964)

7.5 J. L. Christian, "Evaluation of Materials and Test Methods at Cryogenic Temperatures", ERR-AN-400, General Dynamics/Astronautics, (December 1963)

7.6 North American Aviation, Inc., Internal Letter, "The Dynamic Elastic Modulus, Shear Modulus and Poissons Ratio for Twelve Engineering Alloys", Rep. No. 1, MPR-4-175-432, (December 1964)

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7.8 Huntington Alloy Products Div., International Nickel Co., "Inconel 718", Current Data Report, (May 1961)

7.9 McDonnell Aircraft Corp., "Evaluation of Inconel 718, Age-Hardenable Nickel-Chromium Alloy", Report A250, Serial No. 1, (December 1963)

7.10 General Electric Co., "Inconel 718", Specification B, (December 1959)

7.11 J. F. Barker, "A Superalloy for Medium Temperature", Metal Progress, (May 1962)

7.12 General Electric Co., "Inconel 718C", Specification B50T68, (May 1960)

7.13 Private Communication with M. P. Buck, Huntington Alloy Division, International Nickel Co.

7.14 T. M. Cullen and J. W. Freeman, "The Mechanical Properties of Inconel 718 Sheet Alloy at 800, 1000 and 1200F", University of Michigan, NASA CR-268, (July 1965)

CHAPTER 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General. The creep and creep rupture properties of Inconel Alloy 718 are influenced by chemical composition and the heat treatment employed. The recommended heat treatment has undergone considerable change since the introduction of the alloy in 1959. For creep rupture applications, the heat treatment currently recommended for all product forms by the major producer of the alloy is given in Chapter 3, Section 3.222, (Ref. 8.1).

In general, the alloy exhibits excellent creep and creep rupture properties up to temperatures of about 1150F and good oxidation resistance up to 1800F. Sheet, annealed at 1750F and aged at 1325F, exhibits good sharp notch stress rupture properties.

An extensive study of the fatigue behavior of thin sheet at temperatures up to 650F has been conducted and the results are reported in detail in Refs. 8.8 and 8.9.

8.2 Specified Properties

8.21 Creep rupture of aged material. AMS 5596A specifies that a tensile test specimen, maintained at 1295 to 1305F while the axial stress specified below is applied continuously, shall not rupture in less than 23 hours. The test shall be continued to rupture. Elongation after rupture, measured at room temperature, shall not be less than 5 percent in 2 inches, (Ref. 8.2).

Nominal Thickness, inch	Stress, ksi
Up to 0.015 inclusive	70.0
Over 0.015	72.5

8.3 Impact

8.31 Izod impact strength at room temperature. 21 ft-lbs, (Ref. 8.4).

8.4 Creep

8.41 Creep and creep rupture data.

8.411 Creep rupture properties for bar and forgings, Table 8.411.

8.412 Effect of annealing temperature on rupture life of sheet, Fig. 8.412.

8.413 Creep rupture data for smooth and sharp notch sheet specimens at temperatures of 800, 1000 and 1200F, Fig. 8.413.

8.414 Creep and creep rupture curves for annealed and aged sheet at 1100 to 1400F, Fig. 8.414.

8.415 Creep and creep rupture curves for cold rolled and aged sheet at 1100 and 1300F, Fig. 8.415.

8.416 Creep and creep rupture curves for cold rolled and aged sheet at 1200 and 1400F, Fig. 8.416.

8.417 Total plastic creep curves at 1100 to 1400F for bar stock, Fig. 8.417.

8.418 Minimum creep rate for sheet at 800, 1000 and 1200F, Fig. 8.418.

8.42 Linear parameter master curves

8.421 Master curve for creep rupture of annealed and aged bar, Fig. 8.421.

8.422 Linear parameter master curves for creep and creep rupture of aged sheet, Fig. 8.422.

8.423 Linear parameter master curves for creep and creep rupture of cold rolled sheet, Fig. 8.423.

8.424 Linear parameter master curve for hot rolled bar, Fig. 8.424.

8.43 Stress relaxation data

8.431 Effect of time and temperature on stress relaxation of hot rolled, annealed and aged bar, Fig. 8.431.

8.432 Residual stress at various temperatures and times for bar, Fig. 8.432.

8.5 Stability

8.51 Effect of stressed exposure at 800F on room temperature tensile properties, Table 8.51.

8.52 Effect of prior exposure at elevated temperatures under stress on tensile properties of sheet, Fig. 8.52.

8.6 Fatigue

8.61 S-N curves for unnotched sheet specimens tested at room temperature, Fig. 8.61.

8.62 Comparison of S-N curves for unnotched and notched sheet at room temperature, Fig. 8.62.

8.63 Stress range fatigue diagram for unnotched sheet at room temperature, 400F and 650F, Fig. 8.63.

8.64 Effect of prior soak at elevated temperatures on S-N fatigue curves at room temperature for unnotched sheet, Fig. 8.64.

8.65 Bending fatigue strength of sheet at 10^7 cycles, Table 8.65.

CREEP RUPTURE PROPERTIES FOR BAR AND FORGING

TABLE 8.411

Source	(Ref. 8.3)			
Alloy	Inconel Alloy 718			
Test	Creep-Rupture, 100 ksi at 1200F			
Form	Pancake Forging		Hot Rolled Bar	
Size	8 in diam.		5/8 in. diam.	
Heat Treatment	A	B	A	B
Smooth, hr	91.4	97.3	69.4	60.1
e, percent	22.5	35.0	10.0	5.5
RA, percent	61.5	61.0	12.0	83.1

A – 1800F, 1 hr + 1325F, 8 hr, FC 100F/hr to 1150F, hold 8 hr, AC
B – 1800F, 1 hr + 1325F, 16 hr

EFFECT OF STRESSED EXPOSURE AT 800F ON TENSILE PROPERTIES

TABLE 8.51

Source	(Ref. 8.7)					
Alloy	Inconel Alloy 718					
Form	0.025 inch Sheet					
Test	Tensile - exposed at 800F, Tested at RT					
Heat Treatment	L or T	Exposure Conditions Stress, ksi	Time, hrs	F_{tu}, (ksi)	F_{ty}, (ksi)	e(2 in), (percent)
A	L	0	0	218	207	9.5
	L	184	1000	224	222	7.0
	L	180	1300	219	205	8.5
	T	0	0	217	204	7.5
	T	188	1100	225	225	8.5
	T	185	1300	221	220	4.5
B	L	0	0	208	173	17.3
	L	170	4463	210	204	15.3
	L	165	1000	208	196	17.3
	L	160	1000	209	191	18.0
	T	0	0	206	173	18.0
	T	175	5180	212	212	14.8
	T	170	3280	208	197	17.5
	T	165	1000	209	202	16.3
C	L	0	0	204	177	20.5
	L	165	4340	200	194	15.8
	L	160	1000	198	189	20.8
	T	0	0	199	168	21.0
	T	160	4340	196	189	18.5
	T	155	1000	194	183	20.0

A CW (24%) + 1325F, 8 hr, FC to 1150F in 10 hr, AC
B CW (24%) + 1750F, 1 hr + 1325F, 8 hr, FC to 1150F in 10 hr, AC
C CW (24%) + 1950F, 1 hr + 1350F, 8 hr, FC to 1200F in 12 hr, AC

BENDING FATIGUE STRENGTH OF SHEET AT 10^7 CYCLES

TABLE 8.65

Source	(Ref. 8.6)					
Alloy	Inconel Alloy 718					
Form	Sheet					
Test	Bending Fatigue Strength at 10^7 Cycles					
Condition	A		B		C	
Stress Ratio	R = -1	R = 0	R = -1	R = 0	R = -1	R = 0
Max. Stress, ksi	43.0	70.0	40.0	69.0	43.0	68.0
Mean Stress, ksi	0	35.0	0	34.5	0	34.0

A CR (10%), as rolled
B CR (10%) + age 1300F, 16 hr
C CR (10%) + annealed + age 1300F, 16 hr

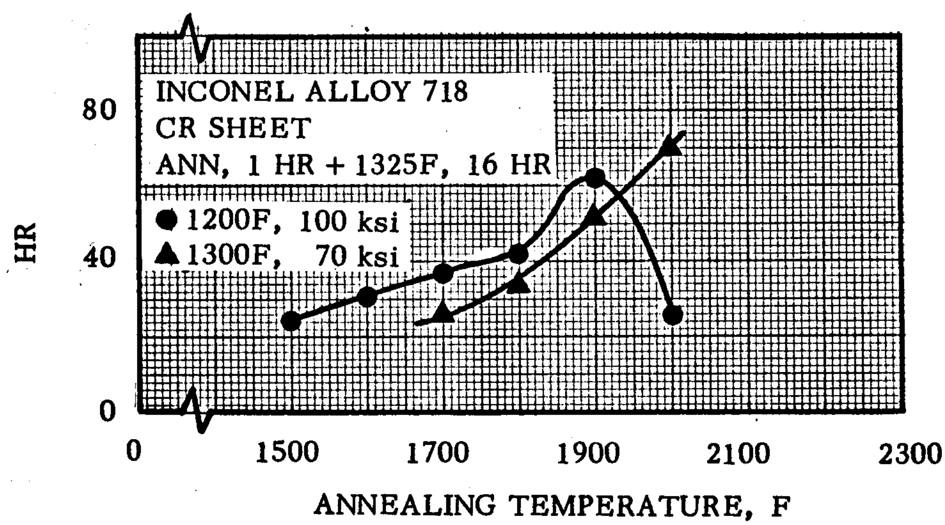

FIG. 8.412 EFFECT OF ANNEALING TEMPERATURE ON RUPTURE LIFE OF SHEET (Ref. 8.3)

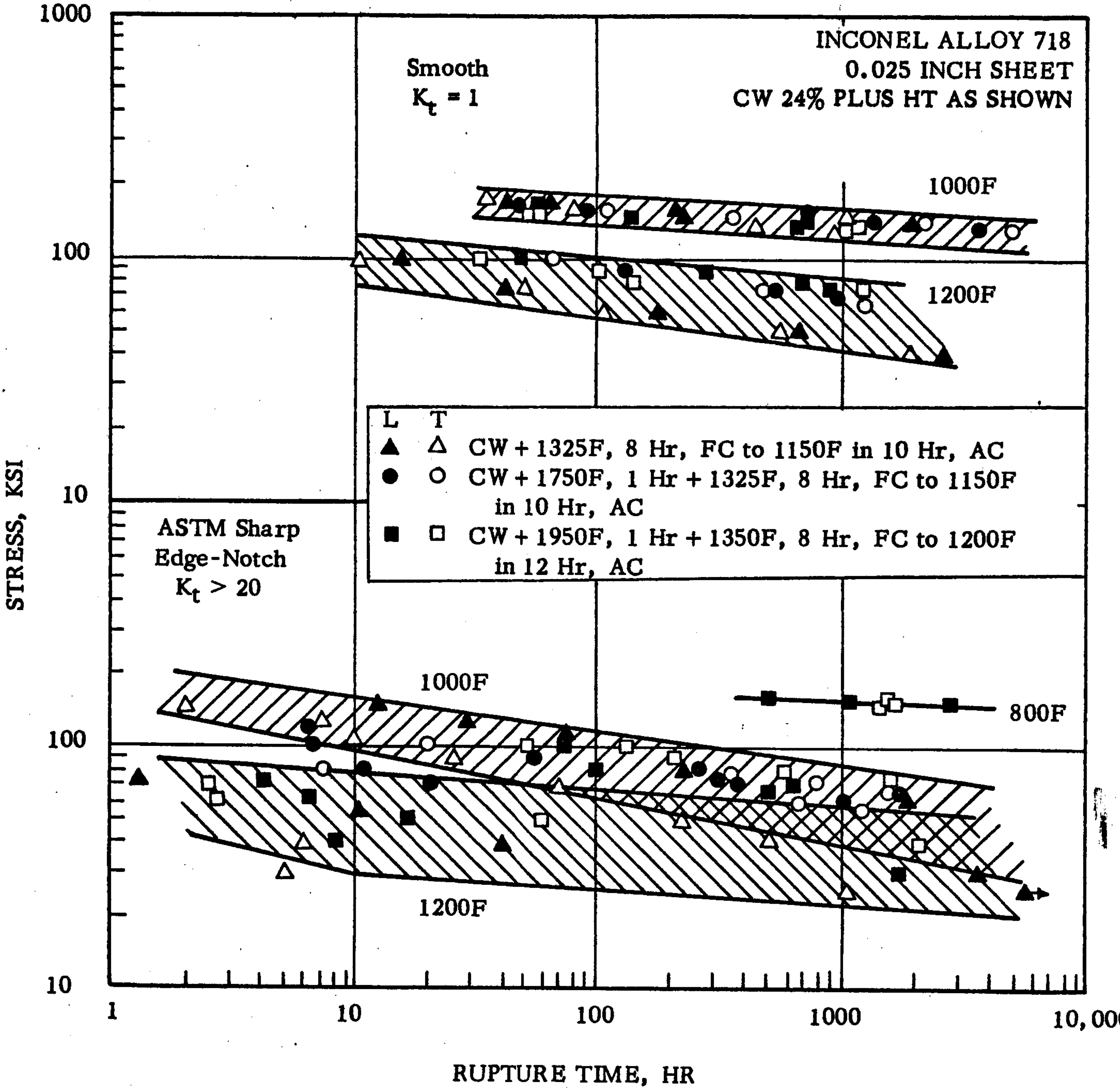

FIG. 8.413 CREEP RUPTURE DATA FOR SMOOTH AND SHARP NOTCH SHEET SPECIMENS AT TEMPERATURES OF 800, 1000 AND 1200F

(Ref. 8.7)

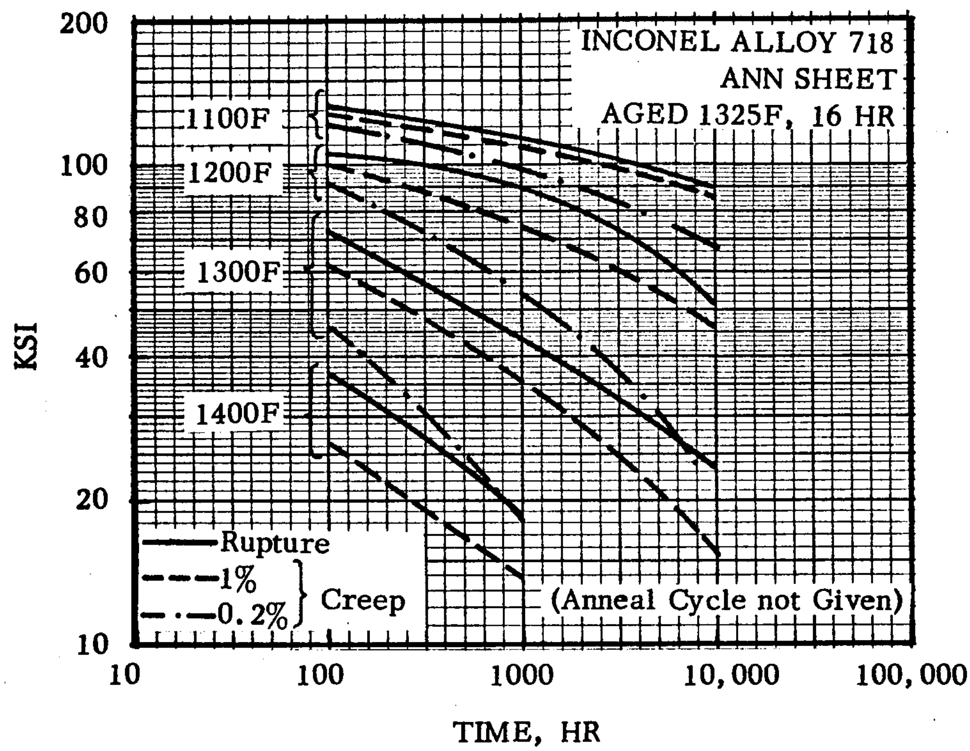

FIG. 8.414 CREEP AND CREEP RUPTURE CURVES FOR ANNEALED AND AGED SHEET AT 1100 TO 1400F (DERIVED FROM LARSON-MILLER PARAMETER) (Ref. 8.5)

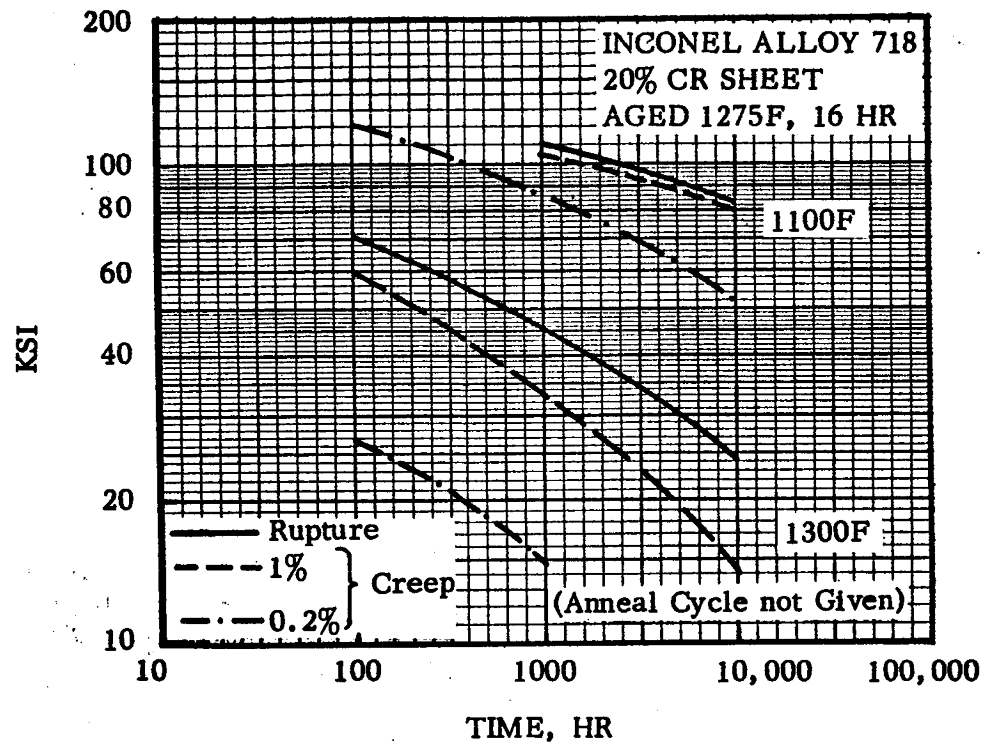

FIG. 8.415 CREEP AND CREEP RUPTURE CURVES FOR COLD ROLLED AND AGED SHEET AT 1100 AND 1300F (DERIVED FROM LARSON-MILLER PARAMETER)

(Ref. 8.5)

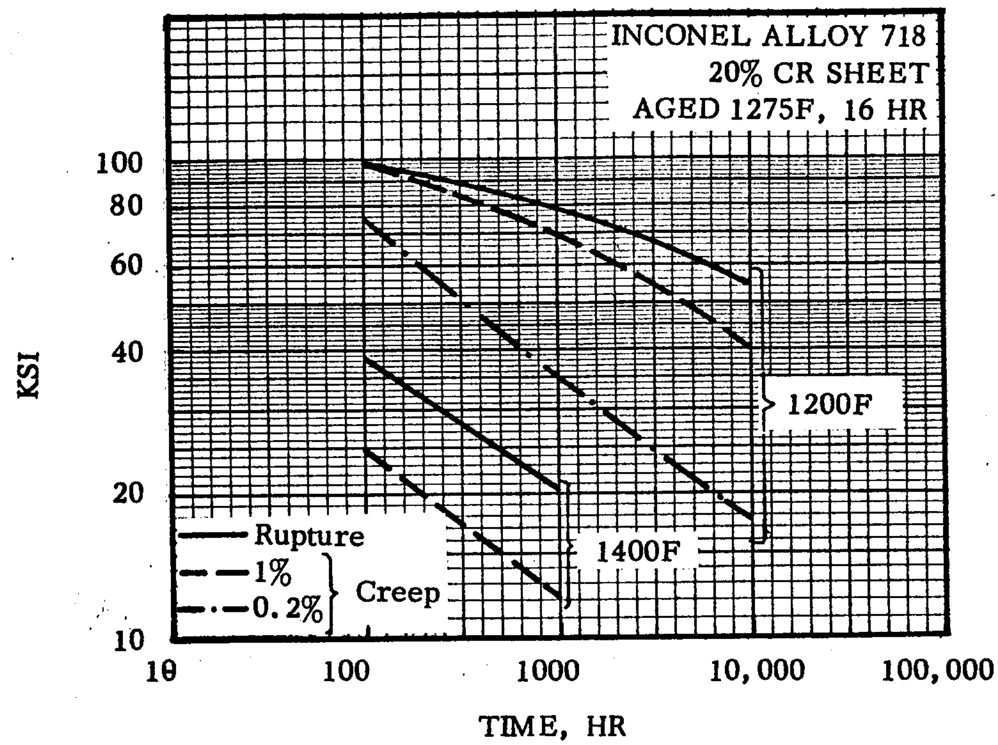

FIG. 8.416 CREEP AND CREEP RUPTURE CURVES FOR COLD ROLLED AND AGED SHEET AT 1200 AND 1400F (DERIVED FROM LARSON-MILLER PARAMETER)

(Ref. 8.5)

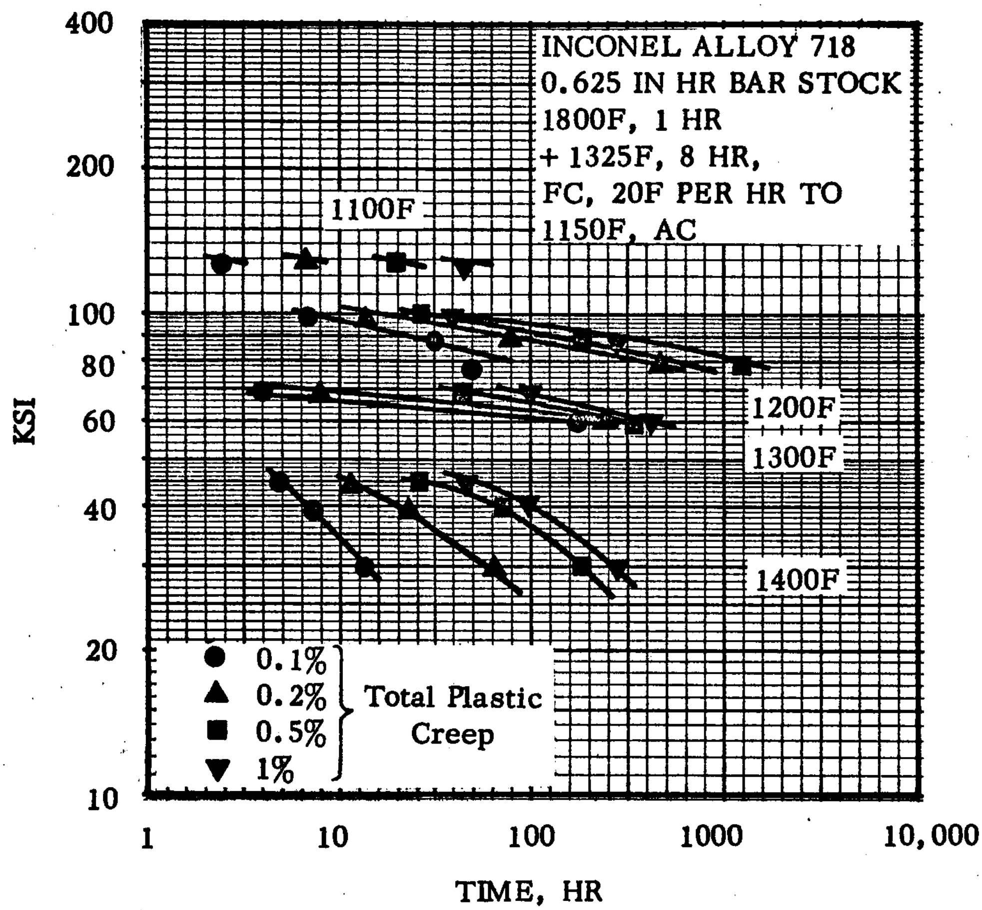

FIG. 8.417 TOTAL PLASTIC CREEP CURVES AT 1100 TO 1400F FOR BAR STOCK (Ref. 8.3)

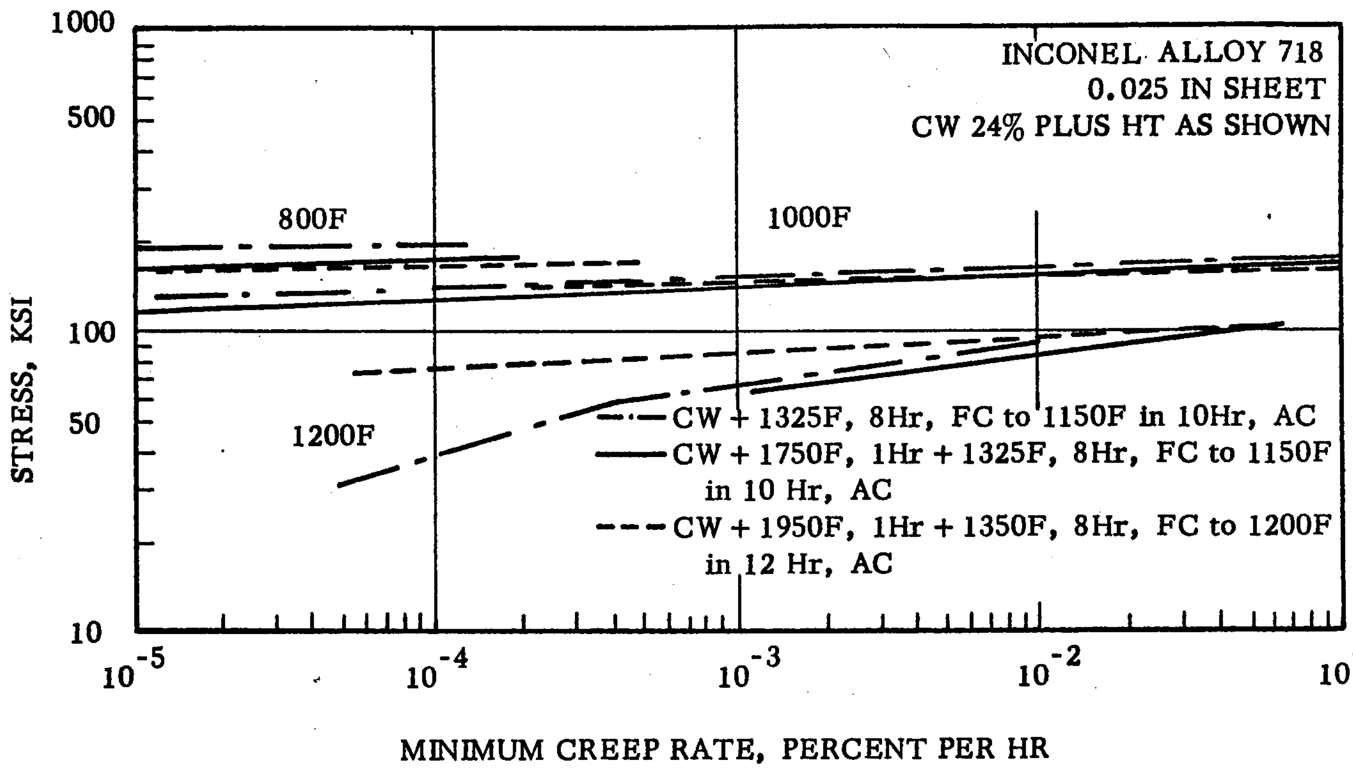

FIG. 8.418 MINIMUM CREEP RATE FOR SHEET AT 800, 1000 AND 1200F

(Ref. 8.

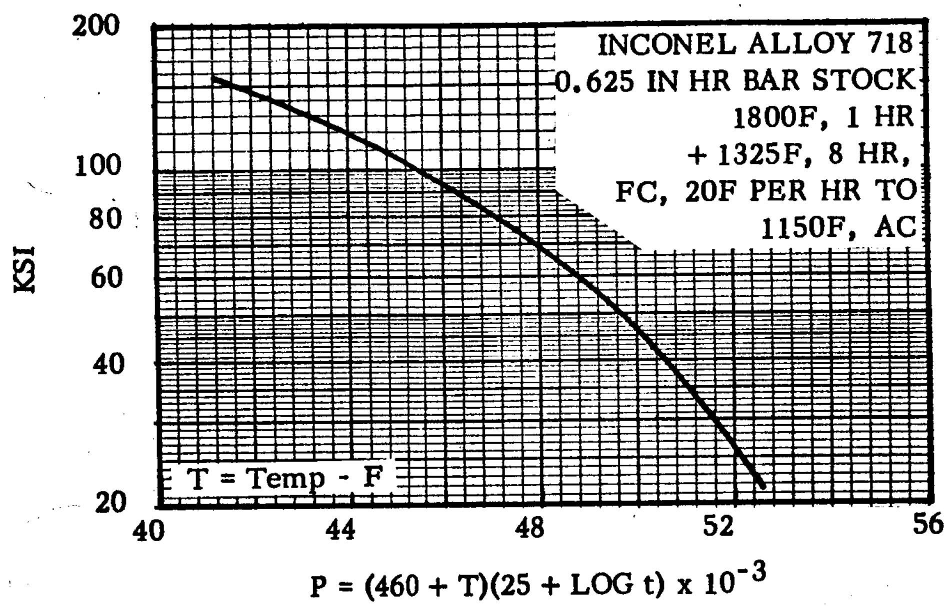

FIG. 8.421 MASTER CURVE FOR CREEP RUPTURE OF ANNEALED AND AGED BAR (Ref. 8.3)

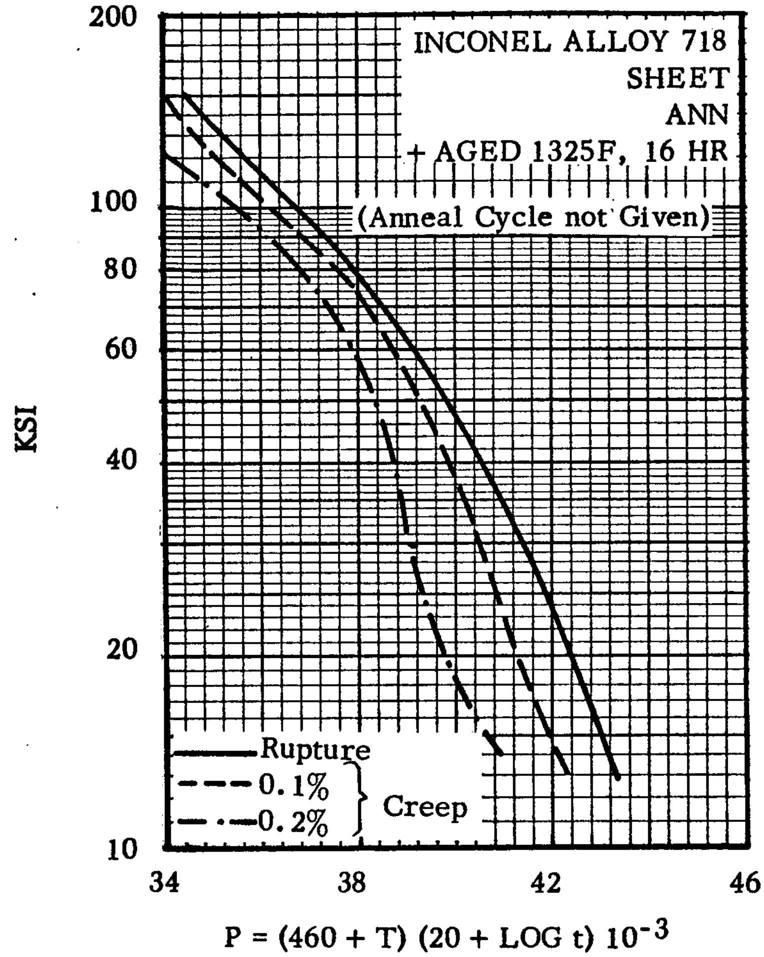

FIG. 8.422 LINEAR PARAMETER MASTER CURVES FOR CREEP AND CREEP RUPTURE OF AGED SHEET (Ref. 8.5)

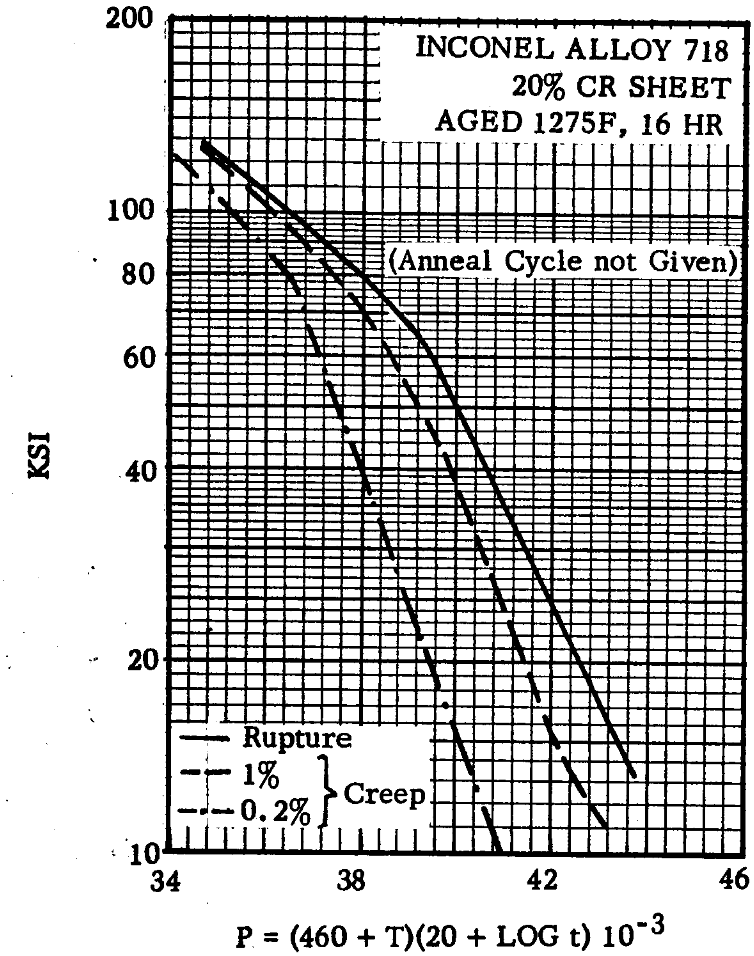

FIG. 8.423 LINEAR PARAMETER MASTER CURVES FOR CREEP AND CREEP RUPTURE OF COLD ROLLED SHEET (Ref. 8.3)

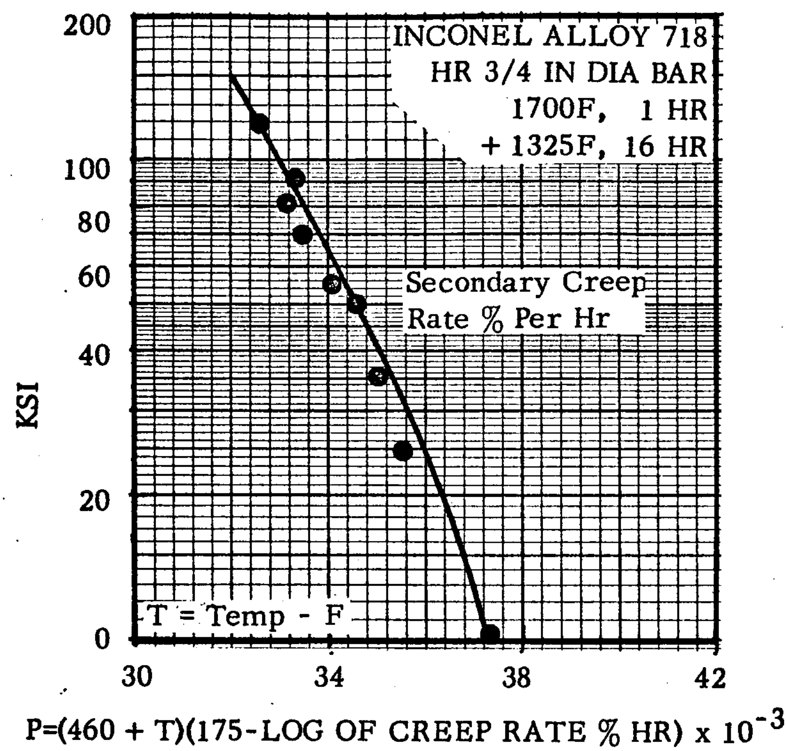

FIG. 8.424 LINEAR PARAMETER MASTER CURVE FOR HOT ROLLED BAR (Ref. 8.5)

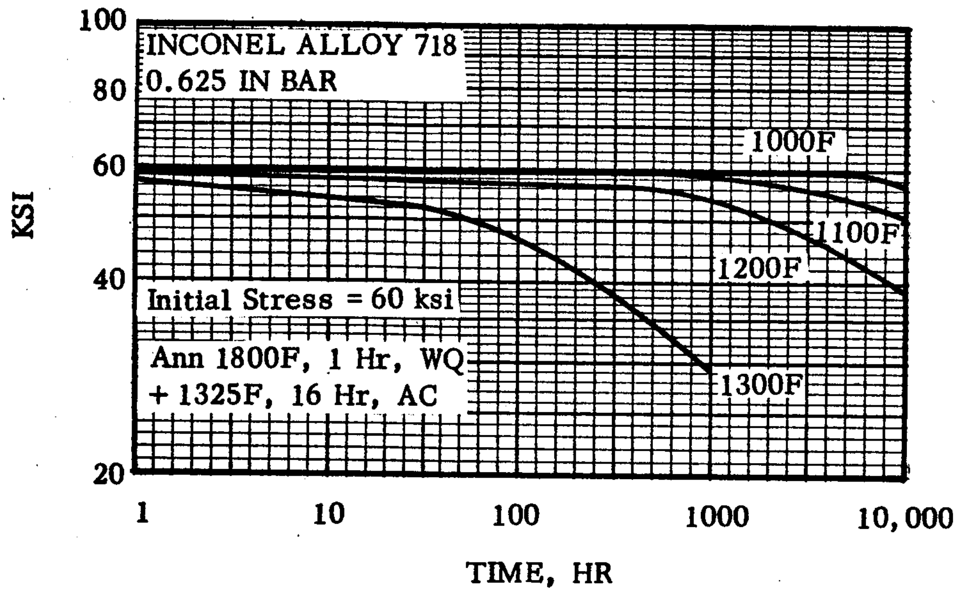

FIG. 8.431 EFFECT OF TIME AND TEMPERATURE ON STRESS RELAXATION OF HOT ROLLED ANNEALED AND AGED BAR (Ref. 8.5)

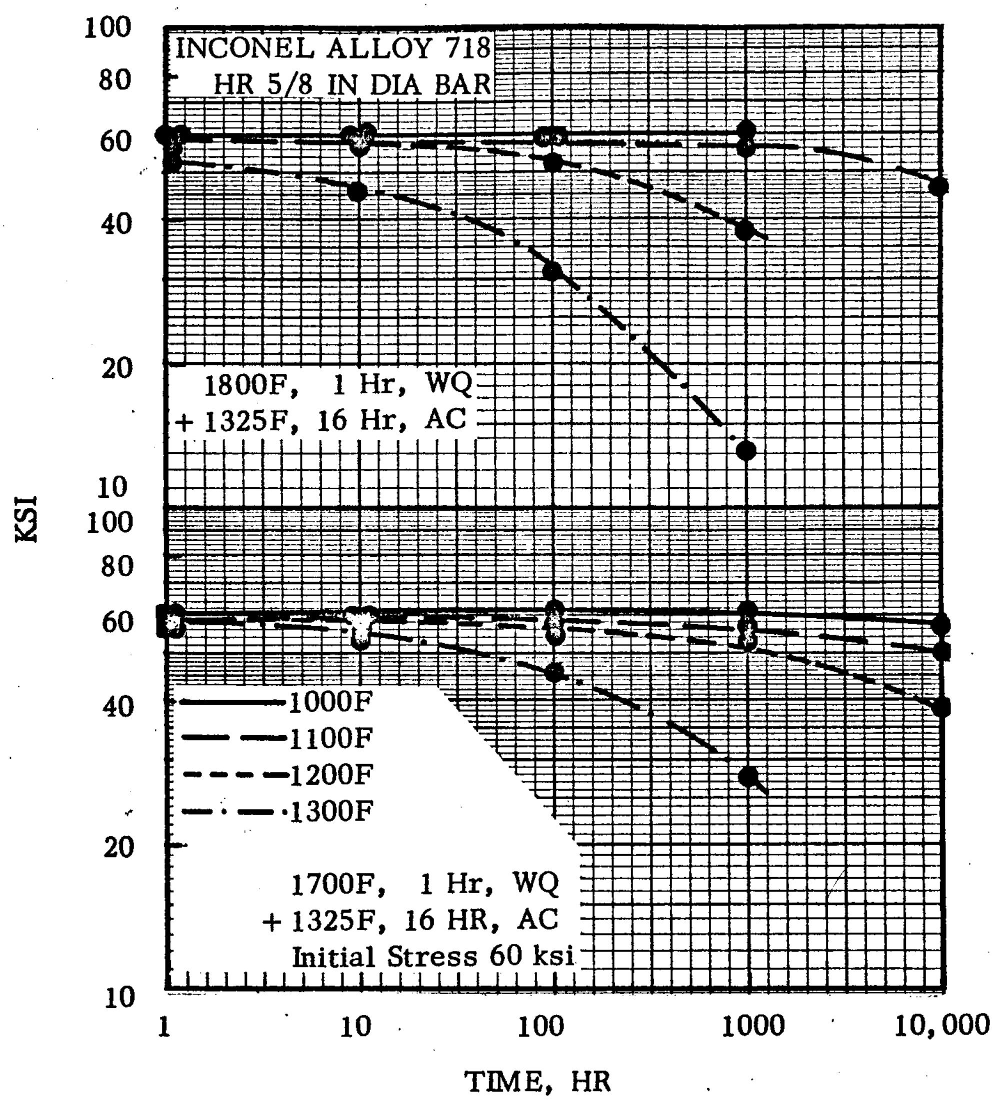

FIG. 8.432 RESIDUAL STRESSES AT VARIOUS TEMPERATURES AND TIMES FOR BAR

(Ref. 8.6)

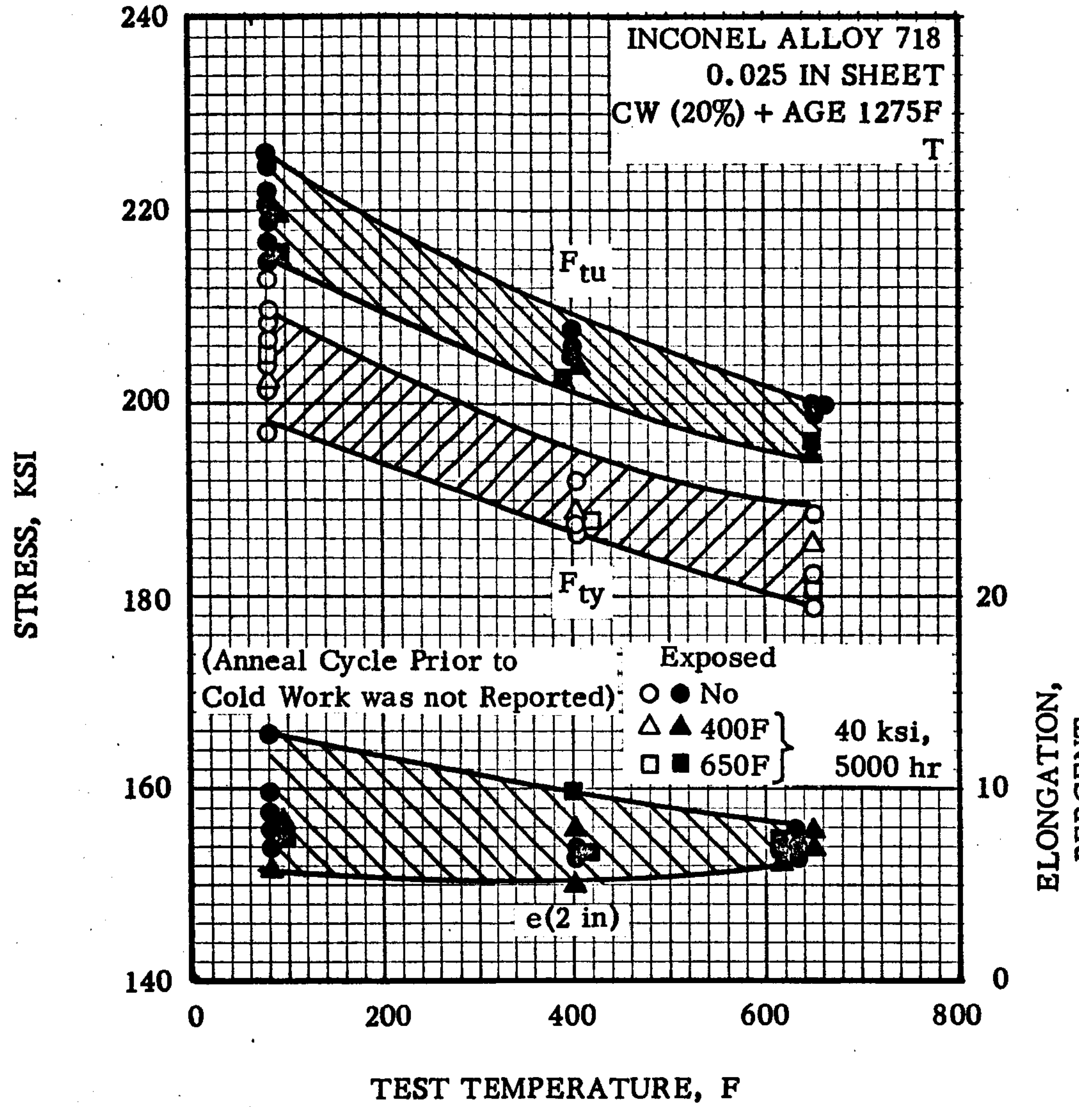

FIG. 8.52 EFFECT OF PRIOR EXPOSURE AT ELEVATED TEMPERATURES UNDER STRESS ON TENSILE PROPERTIES OF SHEET

(Ref. 8.9)

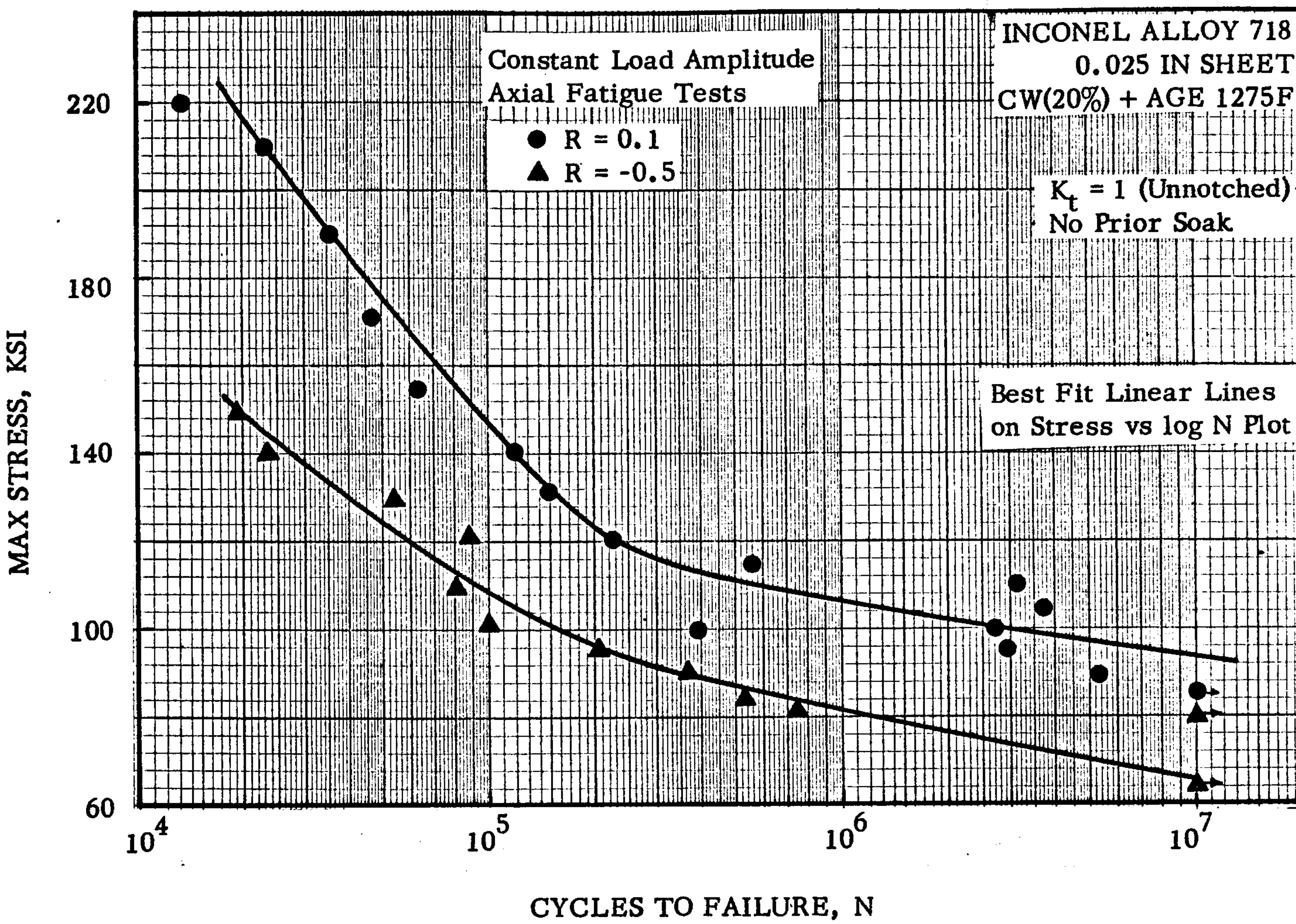

FIG. 8.61 S-N CURVES FOR UNNOTCHED SHEET SPECIMENS TESTED AT ROOM TEMPERATURE

(Ref. 8.8)

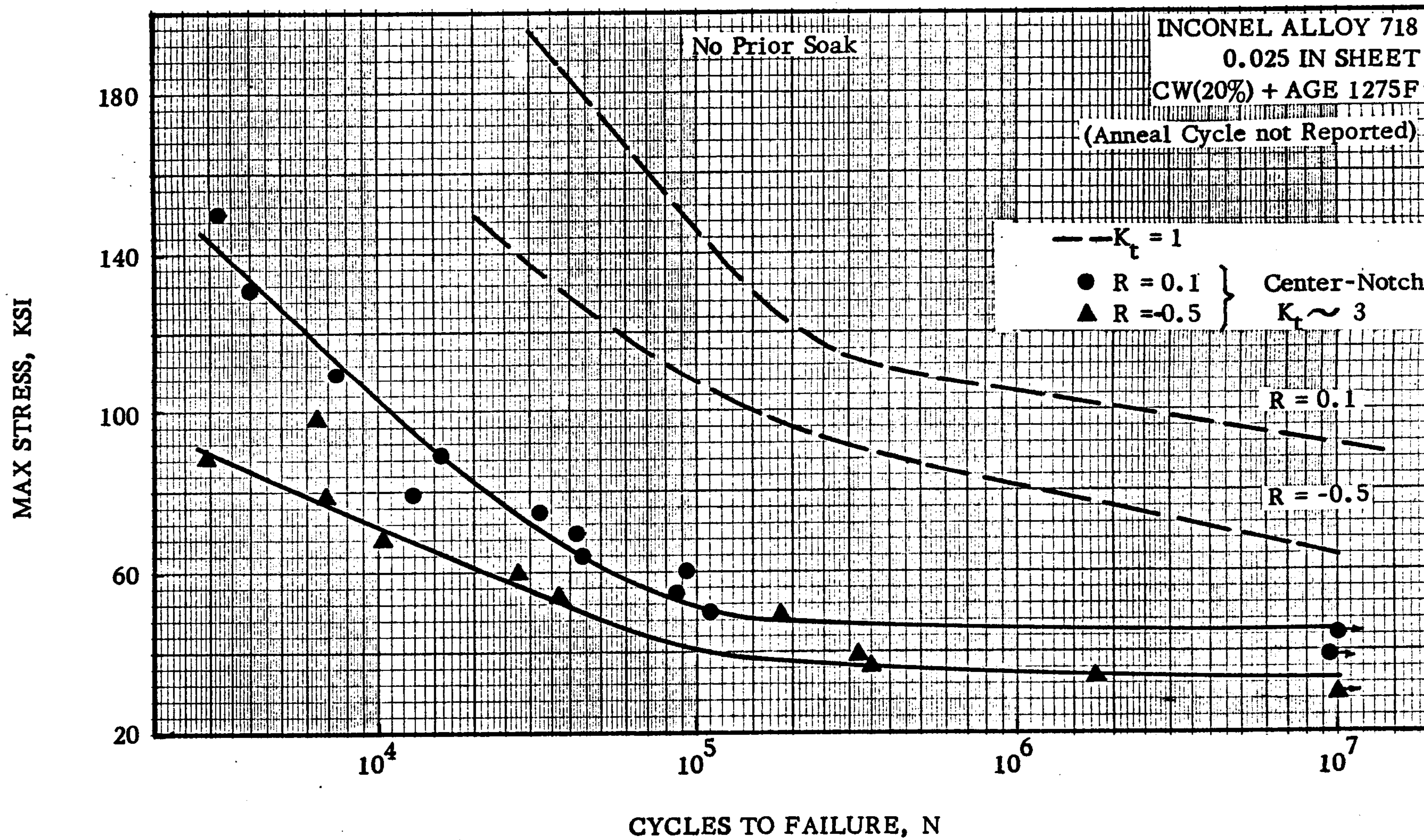

FIG. 8.62 COMPARISON OF S-N CURVES FOR UNNOTCHED AND NOTCHED SHEET AT ROOM TEMPERATURE (Ref. 8.9)

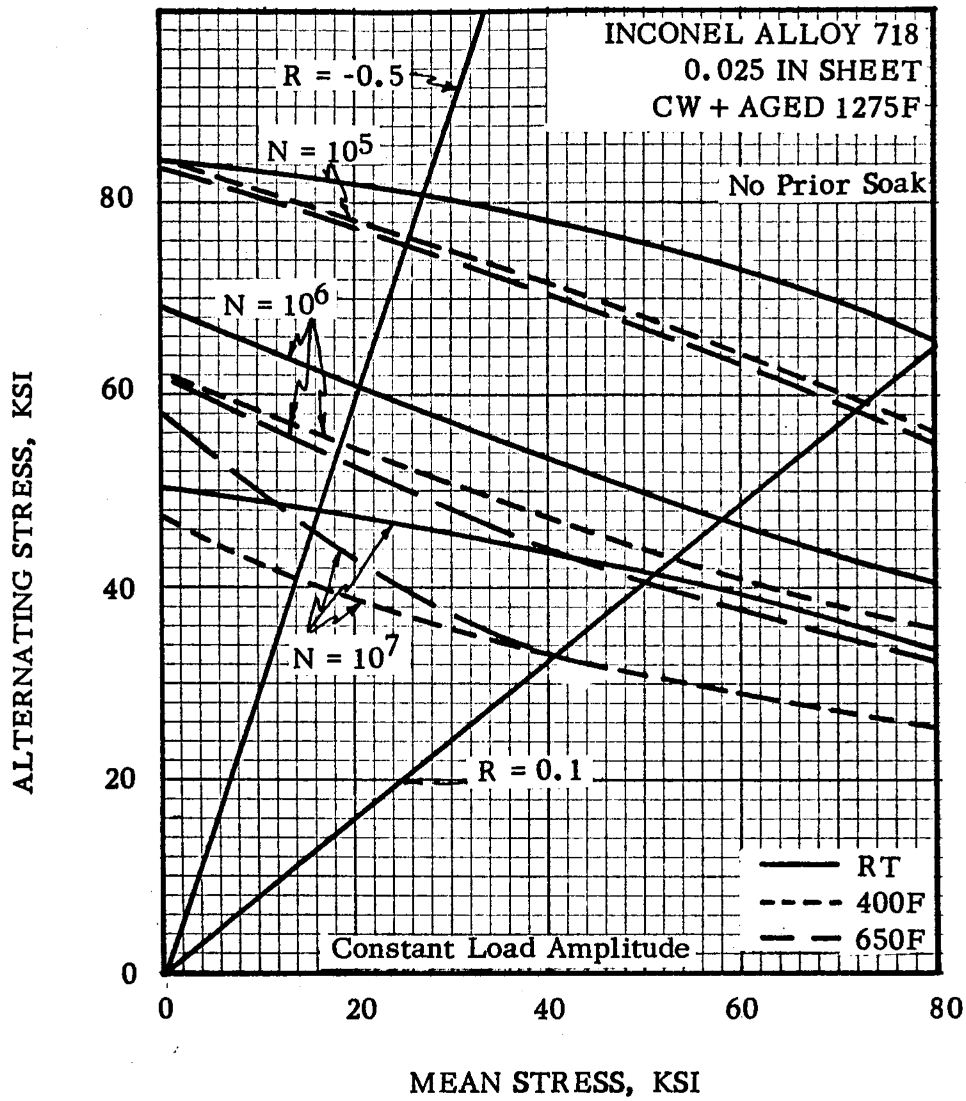

FIG. 8.63 STRESS RANGE FATIGUE DIAGRAM FOR UNNOTCHED SHEET AT ROOM TEMPERATURE, 400F AND 650F (Ref. 8.9)

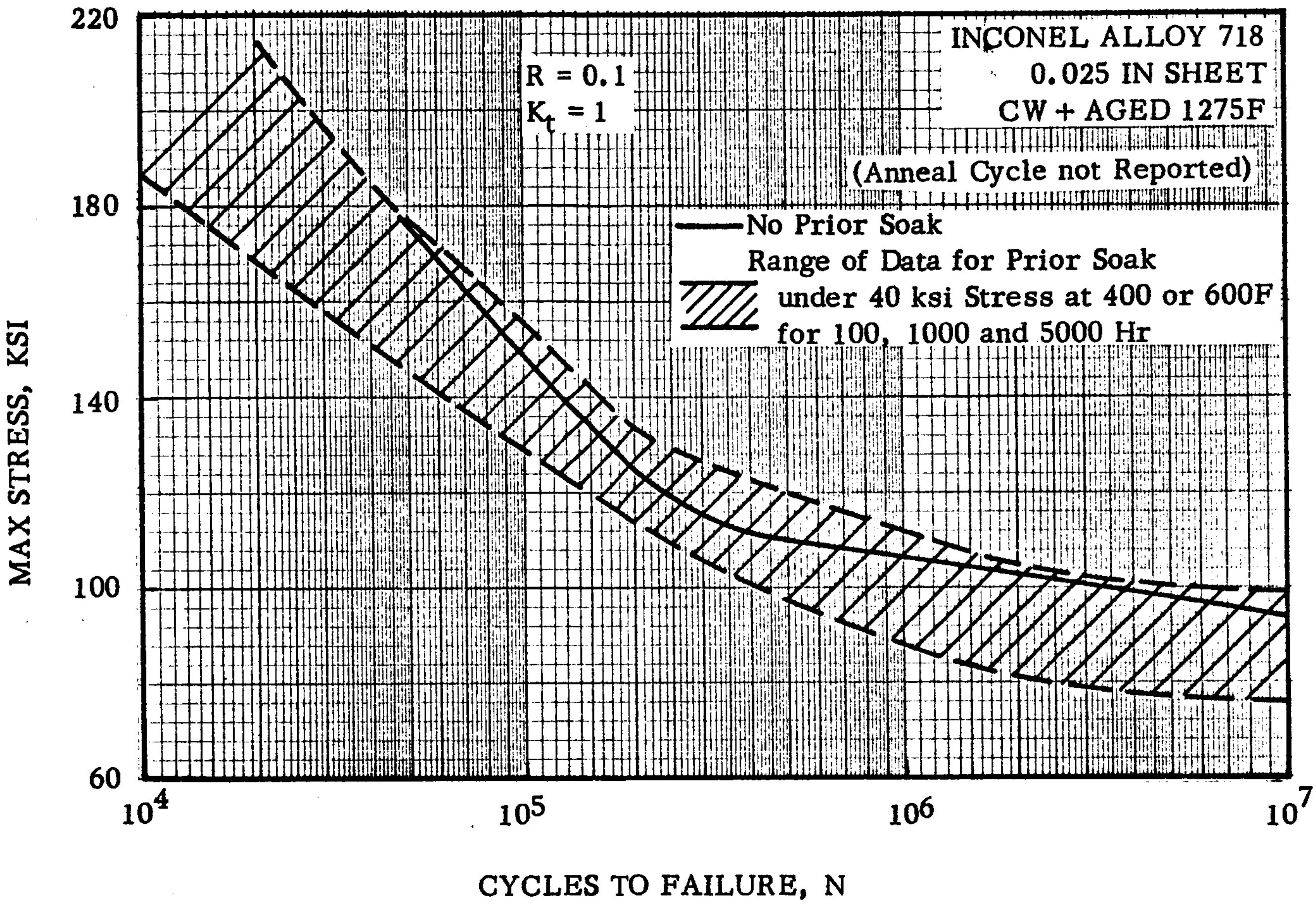

FIG. 8.64 EFFECT OF PRIOR SOAK AT ELEVATED TEMPERATURES ON S-N FATIGUE CURVES AT ROOM TEMPERATURE FOR UNNOTCHED SHEET

(Ref. 8.8)

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8.4 Materials in Design Engineering, Materials Selector Issue, (Mid-October 1965)

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8.6 Alloy Digest, "Inconel 718", Filing Code: Ni-65, Engineering Alloys Digest, Inc., (April 1961)

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CHAPTER 9

PHYSICAL PROPERTIES

9.1 Density (ρ) at room temperature.

Annealed.	0.296 lbs per in^3; 8.18 gr per cm^3
Aged.	0.297 lbs per in^3; 8.21 gr per cm^3, (Ref. 9.1).

9.2 Thermal Properties
9.21 Thermal conductivity (K), Fig. 9.21.
9.22 Thermal expansion, (α), Fig. 9.22.
9.23 Specific heat (c_p). No data found.
9.24 Thermal diffusivity. No data found.

9.3 Electrical Properties
9.31 Electrical resistivity.

Annealed.	127 microhms-cm at room temperature.
Aged.	121 microhms-cm at room temperature, (Ref. 9.1).

9.4 Magnetic Properties
9.41 Permeability. (H = 200). 1.001 at 70F for annealed or age hardened products, (Ref. 9.2).
9.42 Susceptibility.
9.43 Curie Temperature.

Annealed.	$<$ -320F,
Aged.	-170F, (Ref. 9.2).

9.5 Nuclear Properties.

9.6 Other Physical Properties
9.61 Emissivity.
9.62 Damping capacity.

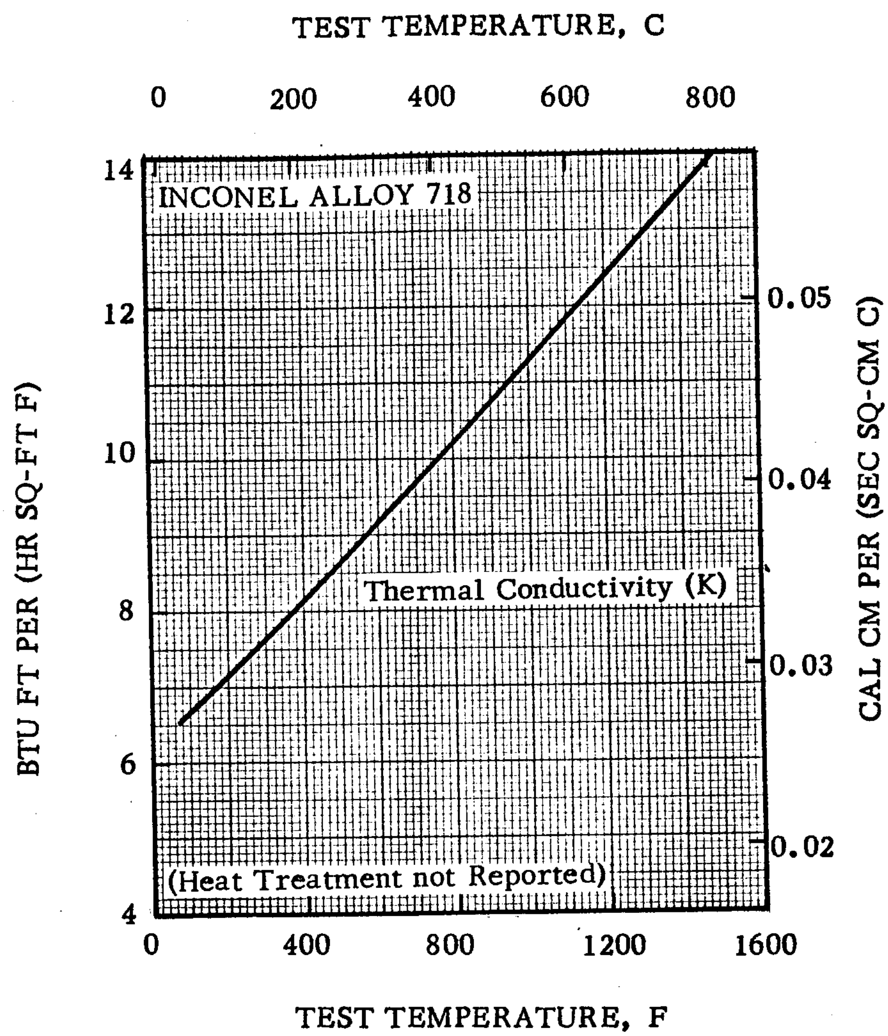

FIG. 9.21 THERMAL CONDUCTIVITY

(Ref. 9.2)

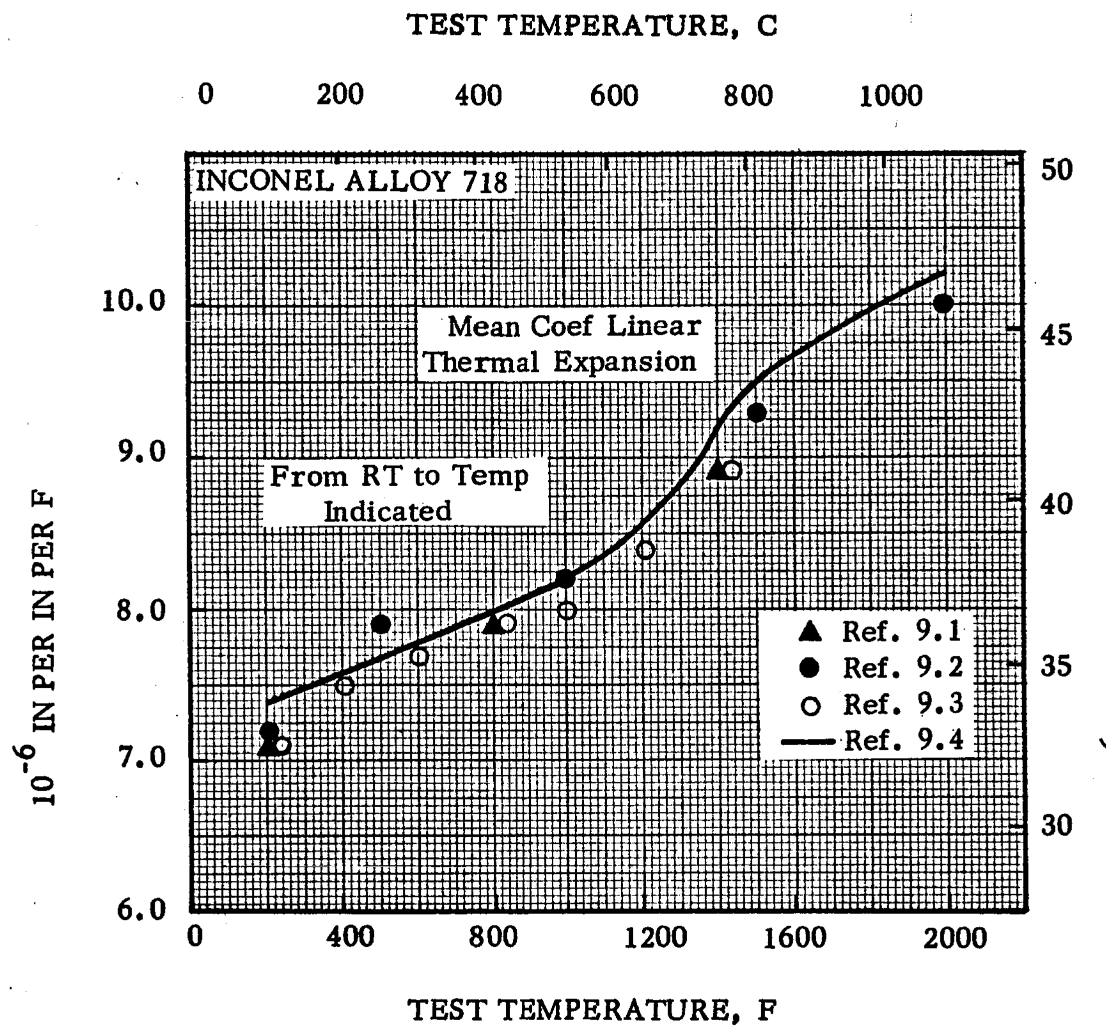

FIG. 9.22 THERMAL EXPANSION

(Refs. 9.1, 9.2, 9.4, 9.3)

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CHAPTER 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Nickel and the high nickel alloys are characterized by their excellent resistance to many kinds of corroding media. In general, these alloys are not attacked by inside or outside atmospheres, unless a sulfurous condition is present. Marine atmospheres may have a slight effect, but rural and suburban atmospheres have no affect on these alloys. Also, they are completely resistant to corrosion by fresh waters. Quiet and stagnant sea water, however, may attack these alloys by causing pitting. Rapid flowing sea water has less effect, (Refs. 10.1 and 10.2).

The complex nickel-base alloys containing closely controlled amounts of several elements, are oxidation resistant. All of these alloys will oxidize, however, at high temperatures if oxygen is present and the rate of oxidation will depend upon alloy composition, temperature, oxygen concentration, diffusion rates and a host of other variables. Light surface oxidation is often not objectionable in these alloys, and may even be beneficial if the oxide is tighly adherent and protective. Intergranular oxidation, on the other hand, can be a serious problem as the penetration of the oxide front reduces the effective cross-section and may also act as a notch to reduce fatigue resistance. Precipitation hardenable nickel-base alloys are particularly susceptible to intergranular oxide penetration. The rate of oxidation is affected by stress and it appears that oxidation rate is increased when a "critical" stress level is reached, (Ref. 10.6).

10.2 Nickel-Chromium-Iron Alloys. This class of alloys, in general, is resistant to corrosion by alkalies, dry gases at room temperature, neutral or alkaline salts, oxidizing acids (at moderate temperatures) and oxidizing alkaline salts. The nickel-chromium-iron alloys are attacked by wet chlorine, bromine, sulfur dioxide and gases of sulfur compounds.

They are moderately resistant to sulfuric and hydrochloric acids at ambient temperatures, but are not normally used with hot or concentrated hydrochloric acid. These alloys have complete resistance to organic acids such as occur in food products, fair resistance to hot concentrated organic acids such as acetic and formic acids, and are highly resistant to fatty acids at elevated temperatures, (Refs. 10.1 and 10.2).

10.3 Resistance of Inconel Alloy 718. Comprehensive information on the corrosion resistance of this particular alloy does not appear to be available as yet. It has been reported, however, that the alloy has excellent resistance to oxidation at temperatures up to 1800F, (Ref. 10.3) and that successful use of the alloy in sea water has been accomplished, (Ref. 10.4).

The chloride stress corrosion susceptibility of Inconel Alloy 718 (and numerous other alloys) has been investigated by the Douglas Aircraft Company, (Ref. 10.5). Unnotched sheet specimens were tested by alternate immersion in synthetic sea water and also in 5 percent salt spray tests under stress up to 90 percent of F_{ty}. Precracked specimens were tested by alternate immersion. Sheet conditions included the base temper (aged condition), aged plus exposure at 650F for 1000 hours, a braze cycle heat treatment (BCHT) and BCHT plus TIG welded with Inconel 718 filler metal. Room temperature tensile data for the various sheet conditions are given in Table 10.1. Table 10.2 presents the results of the stress corrosion tests by alternate immersion in sea water and 5 percent salt spray. The braze cycle heat treatment is illustrated in Fig. 10.1.

The results of this study indicate that within the conditions of the tests employed the Inconel Alloy 718 sheet was immune to chloride stress corrosion. None of the specimens failed during stress corrosion testing regardless of temper, welding or surface preparation, nor did any specimens show reduction of mechanical properties due to stress corrosion.

10.31 This alloy, like most nickel-base alloys, is susceptible to sulfur embrittlement or attack by elements such as lead, bismuth, etc. It is, therefore, essential to remove all foreign matter such as grease, oil, etc. from the alloy prior to any heating operation, (Ref. 10.3).

10.4 Protective Measures. Surface protection is usually not required when the alloy is used in the temperature range from -320F to 1300F for many service applications. However, surface treatments have been developed to improve some of the characteristics of nickel-base alloys, and these are discussed further in Chapter 11.

RESULTS OF STRESS CORROSION TESTS ON SMOOTH SHEET SPECIMENS

TABLE 10.2

Source	(Ref. 10.5)			
Alloy	Inconel Alloy 718			
Form	Unnotched 0.025 inch sheet specimens (c)			
Test	Stress Corrosion (d)			
Exposure under stress of 90% of F_{ty}	Alternate Immersion A		Salt Spray B	
Material Condition	F_{tu}, (ksi)	e(1 in), (percent)	F_{tu}, (ksi)	e(1 in), (percent)
Aged (a)	205.7	19.4	-	-
Aged + 1000 hr at 650F	206.8	17.9	206.9	19.9
Braze cycle heat treat (BCHT)	198.2	18.0	-	-
BCHT + welded (b)(e)	138.7	4.4	142.5	5.0

A Alternate immersion in synthetic sea water for 1000 hr. Sustained stress of 90% F_{ty} during exposure.

B 5% salt spray for 1000 hr. Sustained stress of 90% F_{ty} during test.

(a) 1325F, 8 hr, FC to 1150F, hold total of 26 hr.

(b) Welded specimens failed at edge of weld metal during tensile test.

(c) All specimens were transverse.

(d) Each value is average of 4 tests.

(e) BCHT is shown in Fig. 10.1. Weld specimens were TIG welded using Inconel 718 filler metal.

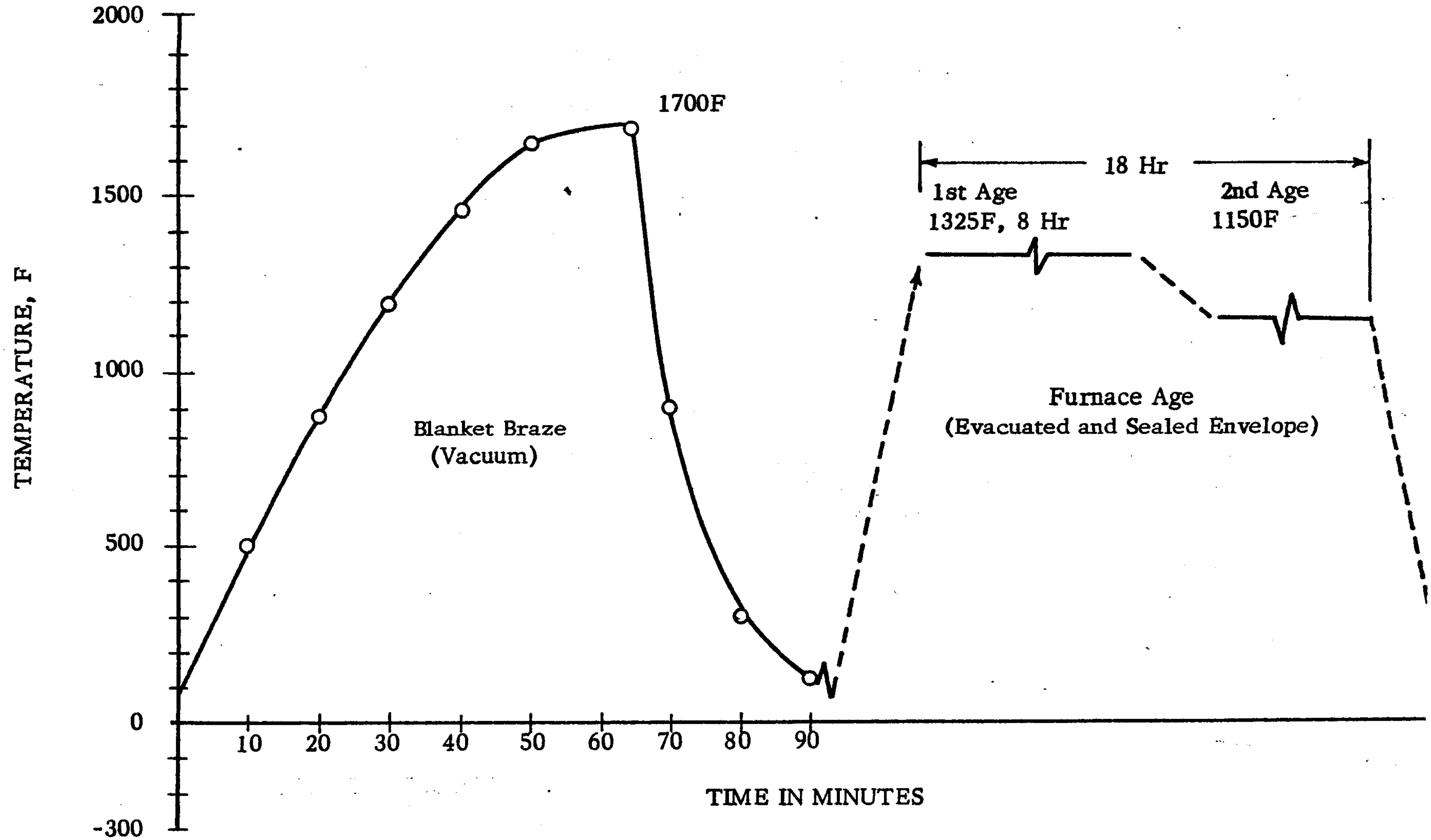

FIG. 10.1 BRAZE CYCLE HEAT TREATMENT APPLIED TO INCONEL 718 SHEET

(Ref. 1

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CHAPTER 11

SURFACE TREATMENTS

11.1 General. A number of surface treatments have been developed that result in improved characteristics in nickel-base alloys. Among the characteristics that can be improved are lubricity, resistance to corrosive attack by oxidizing and/or sulfur-containing atmospheres, and resistance to wear, erosion and fatigue. These treatments may be grouped into two general categories; mechanical treatments and coating treatments, (Ref. 11.1).

11.2 Mechanical Treatments. Mechanical surface treatments such as burnishing, peening, explosive hardening and planishing are not used to any great extent for nickel-base alloys. When used, however, they serve a variety of functions from improvement of surface finish to increasing fatigue strength and surface hardness. Improvements in mechanical properties result largely from the residual compressive stress introduced into the metal surface by these treatments. Burnishing and planishing are used to improve surface finish, while explosive hardening, peening and planishing are used to cold work the metal and/or to develop residual compressive stresses, (Refs. 11.1 to 11.5). A tabulation of mechanical surface treatments used or considered for use with nickel-base alloys is presented in Table 11.1.

The burnishing of nickel-base alloys is accomplished in a manner similar to that used for other metal alloys, except that the work hardening characteristics of nickel-base alloys should be taken into account in the burnishing process, (Refs. 11.2 and 11.3).

Experimental studies (Ref. 11.5) have indicated that explosive hardening processes can be applied to nickel-base alloys. As yet, however, commercial application of these processes to nickel-base alloys has not developed to any extent.

Peening is a well known process used to develop compressive stress in a metal surface. This process is not commonly used for nickel-base alloys, but it appears that these alloys do not have characteristics that prevent the use of peening, (Ref. 11.6). It has been shown (Ref. 11.7) that hammer peening can be used to prevent cracking of repair welds made in Rene' 41 and Astroloy upon subsequent reheat treatment.

Planishing is the production of a smooth surface finish by a rapid succession of blows delivered by polished dies, hammers or by rolling in a planishing mill. Most nickel-base alloys can be planished successfully. Roll planishing is a useful mechanical treatment for fusion welds, especially butt-welds.

Since planishing is actually a type of cold-forming operation, a roll-planished weld is effectively cold worked. With nickel-base alloys that work harden readily, the degree of working can be such as to effect a considerable increase in the strength of a weld joint, (Refs. 11.1 and 11.8). Also in some cases, it may be possible to impart sufficient cold work to a weld for it to recrystallize when subsequently heated to an annealing temperature. In this way, the weld grain structure becomes that of a wrought material and is more homogeneous. This technique has been applied to Inconel Alloy 718 fusion butt-welds in sheet metal components, (Ref. 11.9).

Very little specific information is available on mechanical surface treatments as applied to Inconel Alloy 718 products. It would be expected, however, that these treatments can be successfully applied to this alloy.

11.3 Surface Coating Treatments. Coating treatments for nickel-base alloys include diffusion coating, electroplating, electroless plating, hard-facing and treatments for purpose of lubrication.

Most diffusion coatings used in the United States, for nickel-base alloys, are rich in aluminum. They are used primarily to protect the alloy from the degrading effects of service environments. These coatings have not been particularly successful when used for parts subject to sea-air environments where sulfur may also be present (eg. from jet engine fuels). Under these conditions, a severe type of sulfidation attack has been known to occur, (Ref. 11.1). Diffusion coatings, based on boron have been developed in the Soviet Union to obtain very hard cases on nickel-base alloys. Research to develop these and other improved diffusion coatings is currently in progress in this country.

Nickel alloys generally are not electroplated or electroless plated because they often inherently possess the corrosion or wear resistance for which plating is usually applied. Where plating is employed, care must be taken to remove the passive surface film that occurs naturally on these alloys.

Hard facing is the process of applying special hard materials (hard-face alloys) to a metallic part by a welding method or comparable technique. The objective of hard facing is to increase the resistance of a part to abrasion, wear or erosion, corrosion, oxidation, thermal shock or to combinations of these factors. A number of hard facing materials have been developed and they are commonly applied by means of the oxyacetylene torch. This method allows good control of the operation and produces smooth deposits. Other welding techniques and other methods of application, such as metallizing, plasma-arc deposition and flame plating, have been used to apply hard facings. Although hard facing is not often applied to nickel-base alloys, it has been used to improve the resistance of Inconel 600 to steam erosion, (Refs. 11.10 thru 11.13).

Surface treatments have been developed to provide nickel-base alloys with lubricity under conditions of high temperature or high vacuum where oils and greases would deteriorate. These treatments include lead monoxide films, ceramic-bonded calcium fluoride coatings, application of molybdenum disulfide or tungsten disulfide for lubricity at elevated temperatures and vapor deposition of gold for lubricity under high vacuum, (Refs. 11.14 and 11.15).

Although relatively little specific information is available on the application of surface coatings to Inconel Alloy 718, it appears that many of these coating treatments could be applied to this alloy.

A more detailed discussion of surface treatments for nickel-base alloys is available in Ref. 11.1.

MECHANICAL SURFACE TREATMENTS FOR NICKEL-BASE ALLOYS

TABLE 11.1

Source	(Ref. 11.1)		
Surface Treatment	Characteristic Effect	Satisfactory Results with Process Listed	
		Known(c)	Expected(d)
Burnishing	Smooth, mirror-like surface	x	
Planishing	Smooth surface		x
	Cold working of welds	(a)	
Peening	Cold working of welds and wrought components		x
	Crack prevention in welds	(b)	
	Improve fatigue strength		x
	Correct distortion in welds		x
	Improve stress corrosion cracking resistance		x
Explosive hardening	Increase strength of welds		x
	Increase tensile and yield strength	x	

(a) Applied successfully to Inconel 600 and Inconel 718.
(b) Applied successfully to Rene' 41 and Astroloy.
(c) Expected to be successful on other nickel-base alloys also.
(d) Expected to impart noted characteristic to nickel-base alloys.

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CHAPTER 12

JOINING TECHNIQUES

12.1 General. Inconel Alloy 718 can be joined satisfactorily by fusion and resistance welding techniques and by brazing. Adhesive bonding and mechanical fasteners of various kinds may also be used where strength to weight ratio of the part is not critical.

12.2 Welding. In general, the alloy exhibits excellent weldability and allows considerable flexibility in the control of welding procedures. These characteristics and the relative ease of welding this alloy may be attributed to its sluggish response to thermal treatments, (See Chapter 3). In particular, its relatively slow aging response permits welding without the serious danger of cracking caused by rapid hardening during the heating and cooling portions of the weld process.

12.21 Fusion Welding. Most fusion welding of this alloy has been done by the "tungsten-inert-gas" (TIG) process. Welding by the "metal-arc-consumable electrode" (MIG) method and by electron-beam techniques have also been used but to a much lesser extent. Shielded metal-arc and submerged arc processes are apparently not employed for this alloy at present, (Ref. 12.1). Several users associate weld cracking problems with a high solution annealing temperature. One source reports that a direct relationship exists between the tendency to form microfissures and the solution annealing temperature. With increase in solution annealing temperature, (and hence grain size) the tendency to form microfissures increases, (Ref. 12.16).

12.211 Tungsten-Inert-Gas Process. The TIG process has been used to weld material in thicknesses ranging from 0.020 to 1.5 inches. Filler metals may or may not be used. Argon is the commonly used protective gas with helium preferred for deep-penetration welds. Fully efficient weld joints require complete cleaning of joint areas prior to welding, and light inter-layer grinding should be employed between passes. The alloy is similar to other nickel base alloys in that it does not flow readily when molten. Thus, in most joints over about 1/8 inch thick designs which contribute to full joint penetration are necessary. In one study at the General Electric Co., on 1/4 and 1/2 inch plate, difficulty was encountered in obtaining full penetration weld joints. It was concluded that U-groove joints gave the best results with double U-grooves used for the thicker plate, (Ref. 12.1).

In the same study it was determined that the shielding gas used affected the results, especially in thicker plates. Consistent penetration and higher welding speeds were more readily obtained by using helium gas for TIG welding of 1/4 and 1/2 inch plate, and also porosity was reduced. Properly made welds, however, are not affected by the type of shielding gas employed.

Optimum TIG weld settings for plate, when helium shielding gas is used, are presented in Table 12.1.

The effect of shielding gas has also been studied at McDonnell Aircraft Corp. for TIG butt-welds in 0.045 inch sheet. No difficulties were encountered with either helium or argon gas, although helium gas shielding did require less heat input and resulted in cleaner weld appearance. This difference in appearance did not cause any detectable effects. Process settings used in this study are shown in Table 12.2.

A number of filler metals have been evaluated during weldability studies of Inconel Alloy 718 with Rene' 41 and Inconel 718 filler metals receiving the most attention because their use allows the weld metal to respond to aging treatments. Hastelloy W, Hastelloy R-235, Haynes 25, Incoweld A and Inconel 69 have also been investigated, (Refs. 12.1, 12.3, 12.4 and 12.5). It appears from the results of studies made to date that the Inconel 718 and Rene' 41 filler metals are preferred for welds in sheet stock. Shop experience has shown that more process problems have occurred when Rene' 41 filler is used or when welding manually. Thus automatic or semiautomatic welding with Inconel 718 filler is preferred. If manual methods are used, they must be carefully controlled.

Studies of highly restrained welds in thick plate in the range from 0.75 to 1.5 inch have been made, (Ref. 12.3). When TIG welding with Rene' 41 filler was employed, it was concluded that there was no need for weld stress relief prior to aging and that heavy sections can be welded in the fully-aged condition even under restrained conditions. It was also concluded that welds in heavy sections can be repaired without annealing, and that the repair welds could be aged directly with no difficulty. Another investigation at General Electric Co. has indicated that the use of Hastelloy R-235 filler wire produces good weld tensile and rupture properties in 1/4 inch and 1/2 inch TIG welded plate.

TIG welds in 0.025, 0.050 and 0.125 inch sheet, using no filler, were evaluated as part of the Supersonic Transport Research Program, (Ref. 12.2). The results indicated that Inconel 718 showed exceptional welding characteristics for its alloy class. Defect free welds were consistently obtained when the cleaning and welding procedures normally used for nickel-base alloys were employed. Circular patch tests indicated no "hot short" problem and it was possible to make simulated repair welds without cracking. It was determined that the alloy can be welded in the annealed or in the cold rolled (20%) and aged condition. Joint efficiencies determined in this investigation are shown in Fig. 12.1 for "as-welded" joints. Bend tests on welded samples indicated a minimum bend radius of 1t for the 0.025 inch gage and 4t for the 0.125 inch gage.

It has been reported (Ref. 12.2) that for severely strained joints, the low freezing temperature of Inconel 718 filler metal is a serious limitation. For such joints, Rene' 41 filler is preferred.

12.212 Electron-Beam Welding. Limited information is available on the welding of Inconel Alloy 718 by electron-beam techniques. The results of one study indicated that butt-welds can be made in parts up to 0.875 inch thick with commercial equipment and by welding from each side. Weld strengths equal to double-aged base metal were obtained and the welds were more gas-free than the base metal. It was reported that considerably less shrinkage was also encountered in comparison to TIG welds, (Ref. 12.4). Another study (Ref. 12.2) revealed that electron-beam welding of 0.025 to 0.125 inch sheet resulted in room temperature static strength and fracture properties that were higher than those obtained on the same material by TIG methods.

12.213 Mechanical Properties of Fusion Welds. As previously discussed in Chapter 3, Section 3.122, the properties and microstructure of Inconel Alloy 718 are influenced markedly by chemical composition and heat treatment. These factors also influence the properties of weldments in this alloy. Recommended heat treatments and compositions have undergone many changes since the alloy was first developed, and it appears that these and other factors are still being studied to determine optimum conditions. Much of the mechanical property data available on Inconel 718 weldments were obtained under welding conditions and with pre-weld and post-weld treatments that are no longer recommended by the major producers and users of the alloy. Some of these data, however, are presented here to allow comparison of information for different welding conditions and thermal treatments.

In a recent study (Ref. 12.6), the tensile properties of TIG welded 0.25 inch plate were obtained over a range of temperatures from -423 to 1500F. It should be noted that the heat treatment employed in these studies was the higher annealing and aging temperatures recommended by the major producer of the alloy for tensile limited applications (See Chapter 3, Section 3.221). The results of the weld tests are presented in Fig. 12.2 and are compared to the base metal values in this illustration. High weld strengths were obtained up to about 1200F with a sharp decrease at temperatures above 1200F. Cryogenic weld properties were excellent. It was reported that the high weld properties as compared with parent metal properties were probably due to low hardener content in the parent metal plate.

In Fig. 12.3, typical tensile properties of automatic TIG butt-welded sheet are presented for various temperatures. In this investigation mill-annealed material was welded and then given a post-weld age treatment. Most of the failures occurred in the HAZ except at 1800F where all failures were in the parent metal. Little difference in properties was observed when comparing samples welded with Rene' 41 filler metal to those welded with Alloy 718 filler metal. Rene' 41 welds did have a greater hardness gradient across the weld zone. Tensile properties of welded specimens were about equal to parent metal properties, but elongations were lower in all cases.

Hardness values for TIG welded sheet are given in Table 12.3. These include measurements in the parent material and also in the weld and heat affected zones. The investigators (Ref. 12.7) noted that these data are essentially obsolete, as new heat treatments and process controls have been introduced which alter and enhance the welded properties of the alloy.

The ultimate strength of TIG welded unnotched and notched (K_t = 3) sheet specimens at test temperatures from -110 to 650F are presented in Fig. 12.4. The effect of low temperatures on the strength of TIG welded sheet is shown in Fig. 12.5.

The net fracture strength obtained for various weld procedures are compared to original parent metal static strength in Fig. 12.6.

Creep-rupture data for TIG welded plate at 1200 and 1350F is compared to parent metal rupture properties in Fig. 12.7.

Axial tension fatigue properties of TIG welded sheet are presented in Fig. 12.8 for smooth and notched specimens at room temperature. Fig. 12.9 shows fatigue data for TIG welded sheet at various test temperatures from -110 to 650F. Typical weld joint efficiency of TIG welded sheet joints is given in Fig. 12.10.

Electron beam weld tensile properties for sheet at room temperature are shown in Table 12.4.

12.22 Resistance Welding. The alloy can be resistance seam and spot welded if proper precautions are taken. The most severe condition occurs in the spot welding of thin gage (eg. 20 mil) material in the aged condition. This material may be spot welded by using schedules with low heat input and extended weld times with very flat electrode tip radii to help maintain sheet-to-sheet contact, (Refs. 12.1, 12.2 and 12.10).

In one study (Ref. 12.10), spot diameters of 0.100 inch for the spot welding of 0.020 inch sheet and 0.24 inch for 0.060 inch sheet permitted spots as close as 0.188 and 0.500 inch, respectively, before shunting occurred. The minimum edge distance was 0.125 and 0.250 inch, respectively, for these spot weld samples. A comparison was made between age plus welded specimens and weld plus aged specimens, Fig. 12.11. In all cases, the lap shear strength of single spot weld joints was improved by aging after welding. Cross tension results, however, were about 10 percent higher when the aged plus weld procedure was employed. This behavior was also observed in another study as shown in Fig. 12.12 for 0.025 and 0.050 inch spot welded sheet. It has also been observed (Refs. 12.10 and 12.11) that the ductility ratio (cross tension/lap shear) indicated that aging after welding decreased ductility. However, in no case did the ductility ratio fall below 30 percent which is considered to be adequate resistance weld joint ductility.

Typical spot weld machine settings are given in Table 12.5.

A study of resistance seam welding of sheet has indicated that a satisfactory seam weld should be at least twice as wide as the sheet thickness, with at least 30 percent penetration into each sheet, and 20 to 40 percent overlap, (Ref. 12.10). Typical seam weld machine settings for 0.020 and 0.060 inch sheet are given in Table 12.6. Best strength properties were obtained when the seam welded samples were aged after welding.

The effect of temperature on the strength of flash welded bar is shown in Fig. 12.13. Joint efficiency ranged from 100 percent at room temperature to 95 percent at 1400F based on yield strength.

12.3 Brazing. The alloy can be brazed successfully if the proper procedures, normally employed for alloys of this class, are used. The brazeability of Inconel 718 is comparable to that of PH15-7Mo stainless steel and is better than that of alloys containing over 2 percent aluminum plus tantalum.

A study to compare the wettability of Inconel 718 by three nickel-base and three silver-base brazing alloys was conducted at McDonnell Aircraft on 0.045 inch sheet, (Ref. 12.13). In this study, specimen surfaces were prepared by alkaline cleaning and liquid honing before brazing in a vacuum furnace at a vacuum of approximately 3-5 x 10^{-4} mmHg. Various brazing temperatures from 1675 to 2075 were used for times of 10 to 15 minutes.

The results indicated that the nickel base braze alloys (Coast Metals 50, Coast Metals 52 and Coast Metals 56LC) exhibited superior wetting and flow characteristics when applied to Inconel 718. As a result of this study, tests were made to determine room temperature shear strength of joints made with CM52 and CM56LC, (Ref. 12.14). The results are given in Table 12.7. The strongest joints were obtained with a 15 minute brazing cycle. However, it was concluded that long cycles were detrimental due to serious intergranular penetration by the filler metal and adverse thermal effect on the parent Inconel 718 sheet. It has been reported that brazing above 1800F may reduce the ductility of aged Inconel 718 in the temperature range 1200-1500F as shown in Fig. 12.14. The effect of solution treat temperatures on aged parent metal tensile properties is illustrated in Fig. 12.15. These curves indicate that a brazing temperature of 2150F will result in a 15 to 20 percent degradation of aged parent metal properties.

It is recommended that each brazing alloy and procedure selected for use should be subjected to temperature and time surveys to determine the optimum combination of parameters required for satisfactory joints. Specimens of the base metal should accompany the braze specimen throughout the braze cycle and subsequent thermal treatment to determine the effect of the thermal cycling on base metal properties, (Ref. 12.14).

12.4 Adhesive Bonding. Nickel base alloys can be successfully adhesive bonded using presently available techniques and adhesives. Relatively little work has been done on adhesive bonding of these alloys, however, because nickel-base alloys are normally used at temperatures above the present maximum service temperatures of organic adhesives. Inorganic adhesives of sufficient ductility and low enough maturing temperatures have not as yet been developed sufficiently to compete with brazing and welding techniques for these alloys. For special applications, however, where elevated temperature effects, high strength joints and corrosion resistance are not factors, adhesive bonding may have advantages over other joining procedures.

Ref. 12.15 is recommended as an excellent summary of the state-of-the-art of adhesive bonding of nickel-base alloys.

OPTIMUM TIG WELD SETTINGS FOR PLATE WHEN HELIUM SHIELDING GAS IS USED (a)

TABLE 12.1

Source	(Ref. 12.1)					
Alloy	Inconel Alloy 718					
Thickness, in	0.250			0.500 (c)		
Pass number	1	2	3	1	2	3
Current, amp.	70-75	70-75	80-85	90-95	90-95	100-110
Arc voltage (b)	13-15	13-15	14-16	14-16	14-16	15 - 17
Weld speed, in/min	1.5-2.0	1.5-2.0	1.5-2.0	2.0	2.0	2.0
Filler wire, dia, in	0.063	0.094	0.094	0.063	0.094	0.094
Wire feed rate, in/in weld	2	4	4	2	4	4
Torch gas, cu-ft/hr	30	30	30	35	35	35

(a) Joint design: 0.156 root radius, 0.04-0.05 land single U-groove.
(b) Voltages are averages due to erratic nature when using helium.
(c) Five or six passes are needed for 0.5 inch plate.

PROCESS SETTINGS FOR AUTOMATIC TIG WELDS IN SHEET

TABLE 12.2

Source	(Ref. 12.1)	
Alloy	Inconel Alloy 718	
Thickness, in	0.045 Sheet	
Automatic TIG Welding Process	Shielding Gas	
	Argon	Helium
Current, amp.	80	40
Arc voltage, V	8-16	16-18
Weld speed, in/min	8	6-8
Filler wire diam, in	0.030-0.035	0.030-0.035
Wire feed rate, in/min	12-15	8-9
Torch gas, cu-ft/hr	20-24	20
Backup gas, cu-ft/hr	4	4

HARDNESS VALUES FOR TIG WELDED SHEET

TABLE 12.3

Source	(Ref. 12.7)			
Alloy	Inconel Alloy 3/16 inch Sheet-TIG Weld			
Test	Rockwell Hardness Measurements			
Condtion	Filler Metal	Location		
		Weld	HAZ	Parent
As welded	Inconel 718	98B	24C	24C
	Incoweld A	98B	98B	98B
	Hastelloy W	23C	23C	23C
	Haynes 25	98B	98B	98B
	Rene' 41	23C	98B	98B
Weld and anneal 1725F, 1 hr, AC + age 1325F, + 16 hr, AC	Inconel 718	36C	40C	38C
	Incoweld A	32C	43C	40C
	Hastelloy W	24C	40C	40C
	Haynes 25	32C	39C	38C
	Rene' 41	38C	42C	39C

ELECTRON BEAM WELD TENSILE PROPERTIES

TABLE 12.4

Source	(Ref. 12.2)					
Alloy	Inconel Alloy 718 Sheet					
Condition	Aged (a) + Electron Beam Weld (b)					
Orientation	Transverse to Weld Bead					
Test Temp, F	Room Temperature					
Thickness, in	F_{tu}, (ksi)	F_{ty}, (ksi)	Elongation, percent			Notch Strength (ksi) (K_t = 3)
			1/2in	1 in	2 in	
0.025	149	107	7	3.3	1.7	148
0.125	160	113	7	3.5	1.7	164

(a) Aged 1275F, 8 hr, FC at 20F/hr to 1150F, hold 10 hr, AC
(b) Weld schedule for 0.125 inch sheet:

Accelerating voltage	120 Kv
Beam current	8 ma
Travel speed	20 ipm
Beam diameter	0.005 inch
Oscillation width	0.010 inch
Vacuum	1 x 10^{-4} mm Hg

TABLE 12.5

Source	(Ref. 12.10)			
Alloy	Inconel Alloy 718 Sheet			
Machine Setting	Heat-Treat Condition and Material Thickness			
	0.020 in, As Rec	0.020 in, Aged	0.060 in, As Rec	0.060 in, Aged
Preheat heat, %	---	8	---	---
Preheat impulses	---	2	---	---
Preheat time, cycles	---	10	---	---
Weld heat, %	16	16	40	38
Weld impulses	2	2	2	2
Weld time, cycles	4	10	8	8
Current decay heat, %	10	---	35	35
Current decay time, cycles	3	---	6	6
Cool time, cycles	0.5	0.5	1.5	1.5
Squeeze time, cycles	21	21	21	21
Hold time, cycles	50	50	61	61
Weld force, lb	660	750	2850	2900
Forge delay, cycles	11-B (a)	11-B (a)	O-E (a)	O-E (a)
Forge force, lb	1500	1950	5380	5400
Electrode class, RWMA	III	III	III	III
Electrode diam, in	5/8	5/8	5/8	5/8
Electrode radius, in	3	10	5	5

(a) B- beginning of weld; E - end of weld.

TYPICAL SEAM WELD MACHINE SETTINGS

TABLE 12.6

Source	(Ref. 12.10)			
Alloy	Inconel Alloy 718 Sheet			
Machine Setting	Heat-Treat Condition and Material Thickness			
	0.020 in, As Rec	0.020 in, Aged	0.060 in, As Rec	0.060 in, Aged
Weld heat, percent	45	45	65	65
Weld impulses	4	4	8	8
Weld time, cycles	5	5	4	4
Cool time, cycles	0.5	0.5	0.5	0.5
Motor speed	50	50	70	70
Motor rotation,cycl.	5	5	5	5
Drive (a)	---	---	---	---
Tip Force, lb	800	800	2000	2000
Forge time, cycles	5	5	5	5
Wheel class,RWMA	III	III	III	III
Wheel Thickness,in	1/2	1/2	1/2	1/2
Wheel radius, in	3	3	3	--
External cooling	Yes	Yes	No	Yes

(a) Intermittent

AVERAGE SHEAR STRENGTH OF VACUUM BRAZED LAP JOINTS

TABLE 12.7

Source	(Ref. 12.14)			
Alloy	Inconel Alloy 718, 0.043-0.051 in Sheet			
Test Temp, F	Room Temperature			
Braze Metal	Brazing Temp (F)	Brazing Time (Min)	Failure Location	Failure Stress (ksi)
CM 52	1950	15	Base metal	28.2
	2000	15	Braze joint	27.1
	2050	15	Braze joint	19.8
	1950	3	Braze joint	23.3
	2000	3	Braze joint	27.8
	2050	3	Braze joint	27.6
CM 56LC	2050	15	Braze joint	31.0
	2100	15	Base metal (a)	25.5
	2150	15	Base metal (a)	17.2
	2050	3	Braze joint	27.5
	2100	3	Braze joint	23.2
	2150	3	Braze joint	25.6

(a) In fillet. Calculated failure stress.

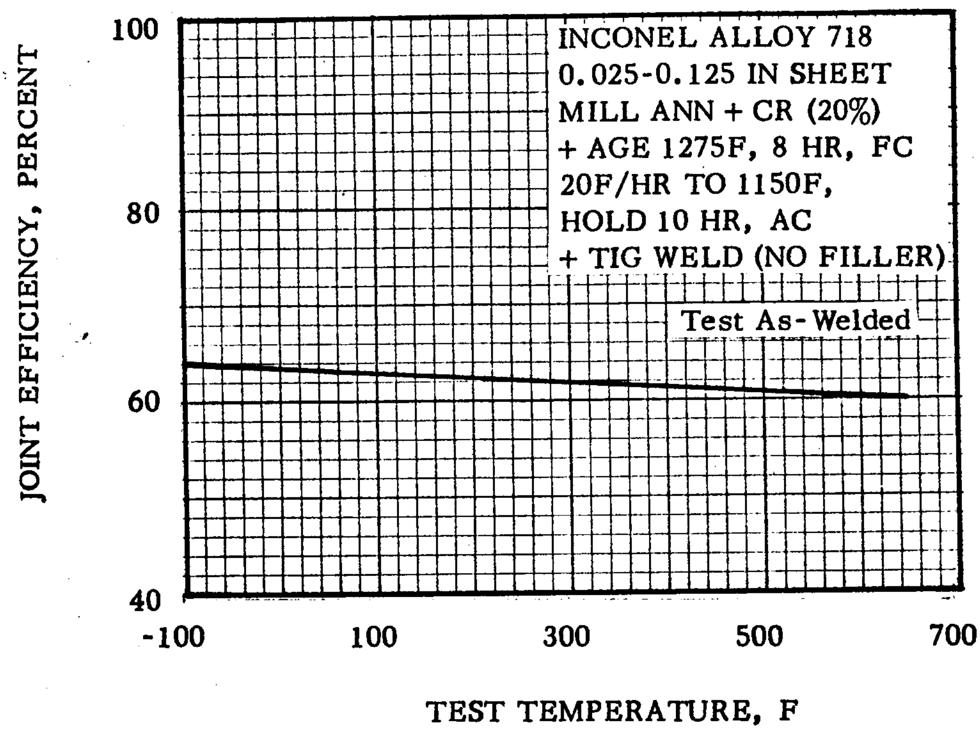

FIG. 12.1 JOINT EFFICIENCY OF TIG WELDS AT VARIOUS TEMPERATURES

(Ref. 12.2)

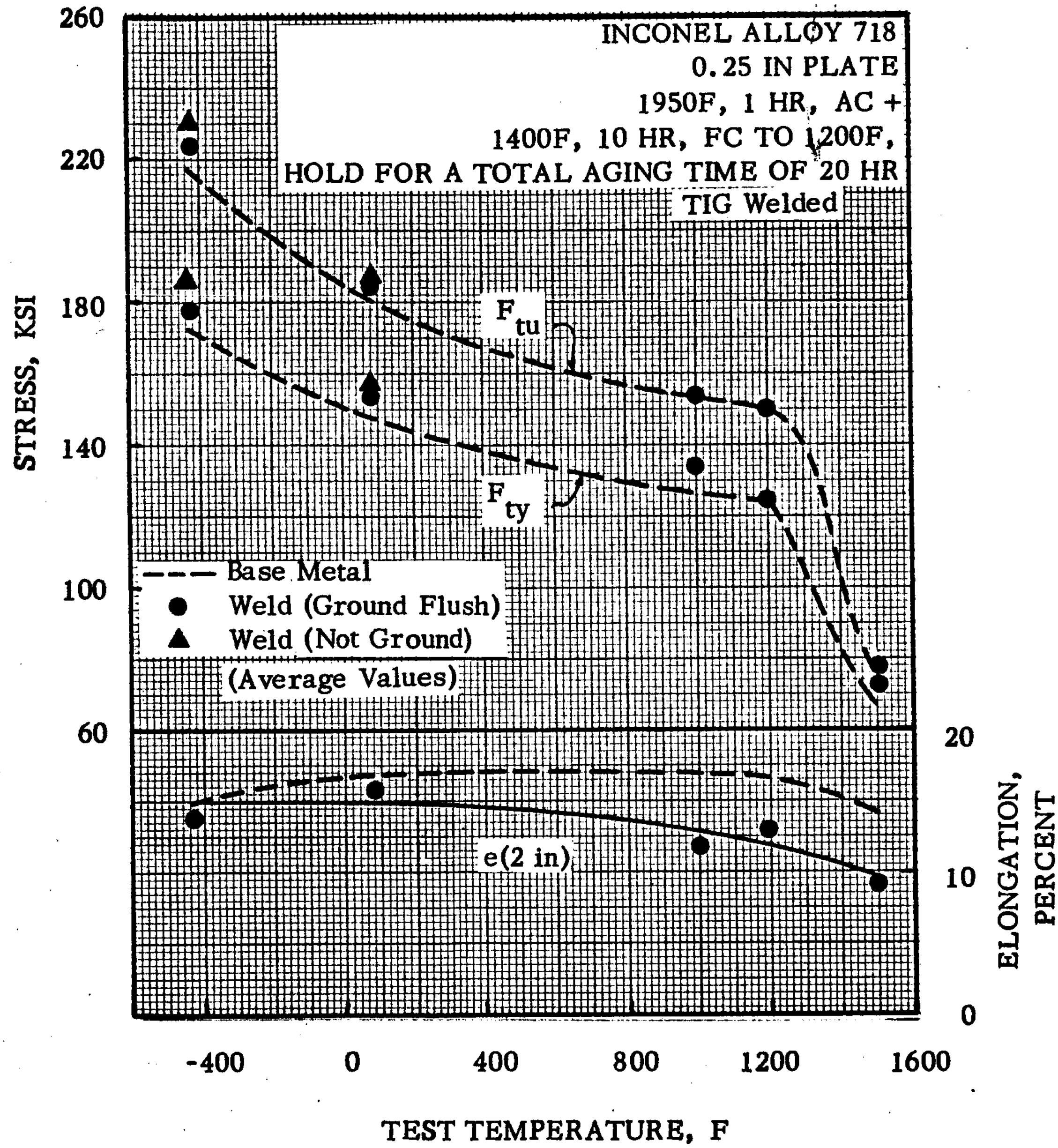

FIG. 12.2 TENSILE PROPERTIES OF TIG WELDED PLATE (Ref. 12.6)

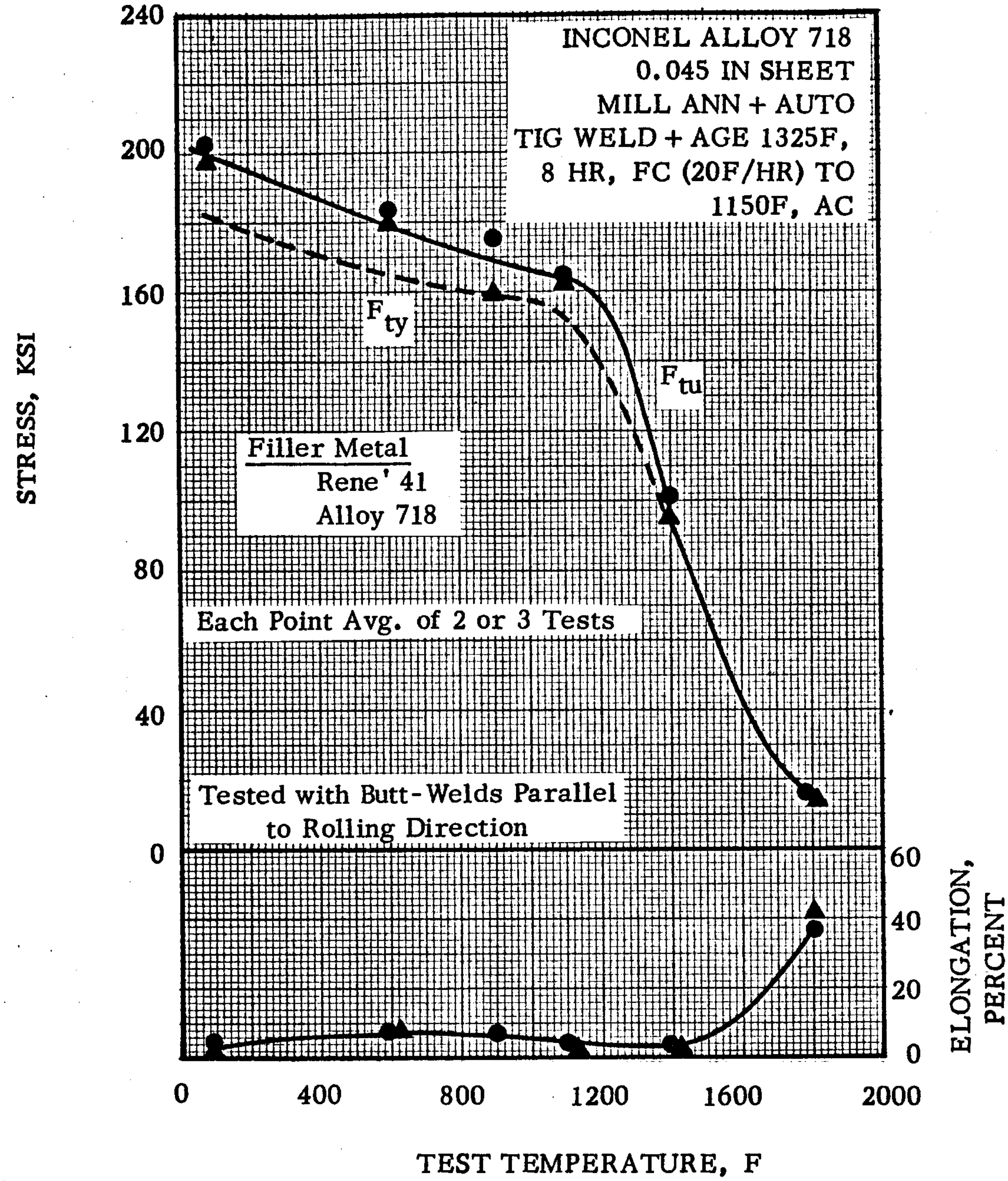

FIG. 12.3 TENSILE PROPERTIES OF AUTOMATIC TIG BUTT-WELDED SHEET AFTER POST-WELD AGING

(Ref. 12.1)

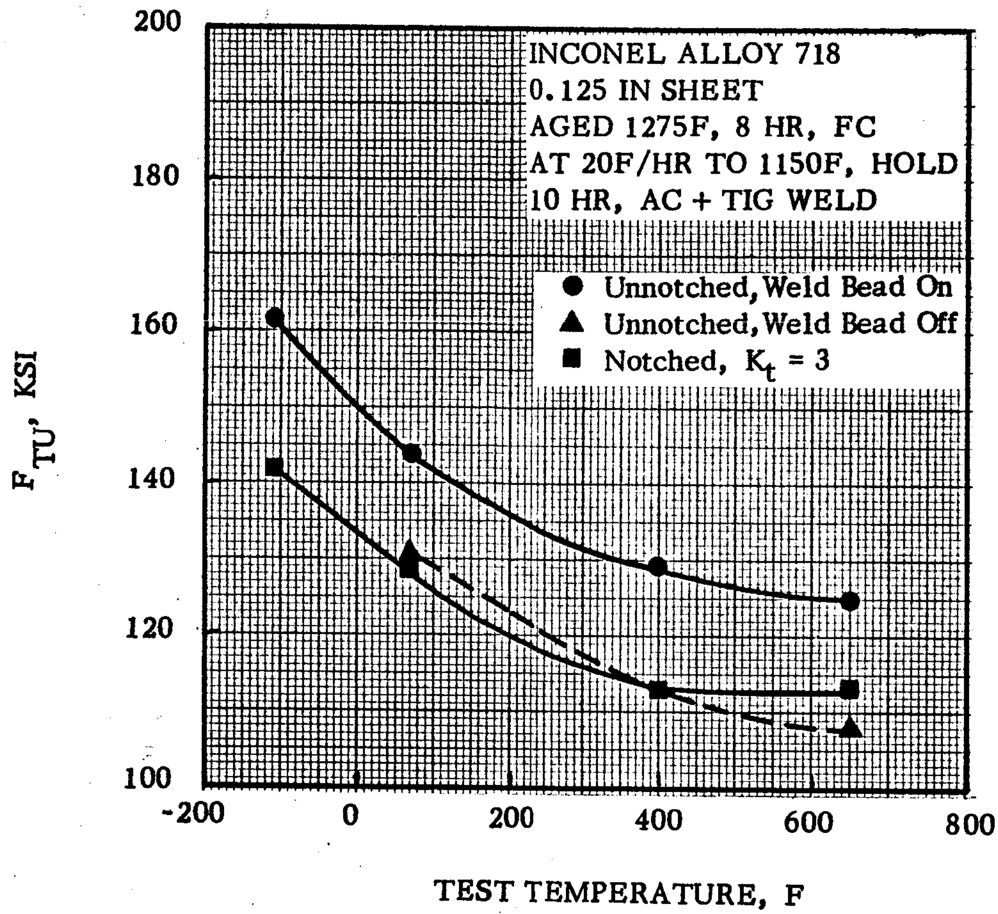

FIG. 12.4 ULTIMATE STRENGTH OF TIG WELDED UNNOTCHED AND NOTCHED SHEET SPECIMENS

(Ref. 12.2)

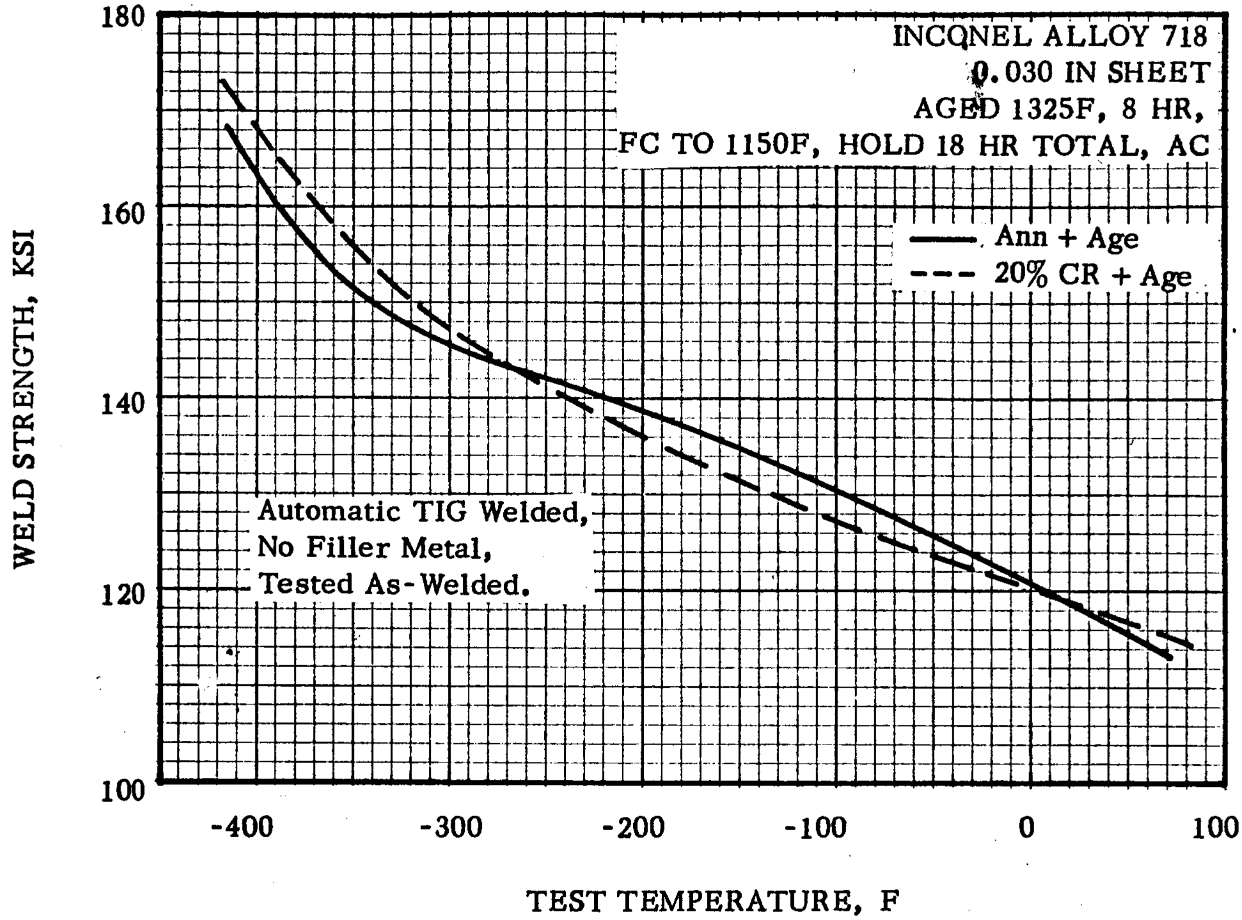

FIG. 12.5 EFFECT OF LOW TEMPERATURES ON THE STRENGTH OF TIG WELDED SHEET

(Ref. 12.8)

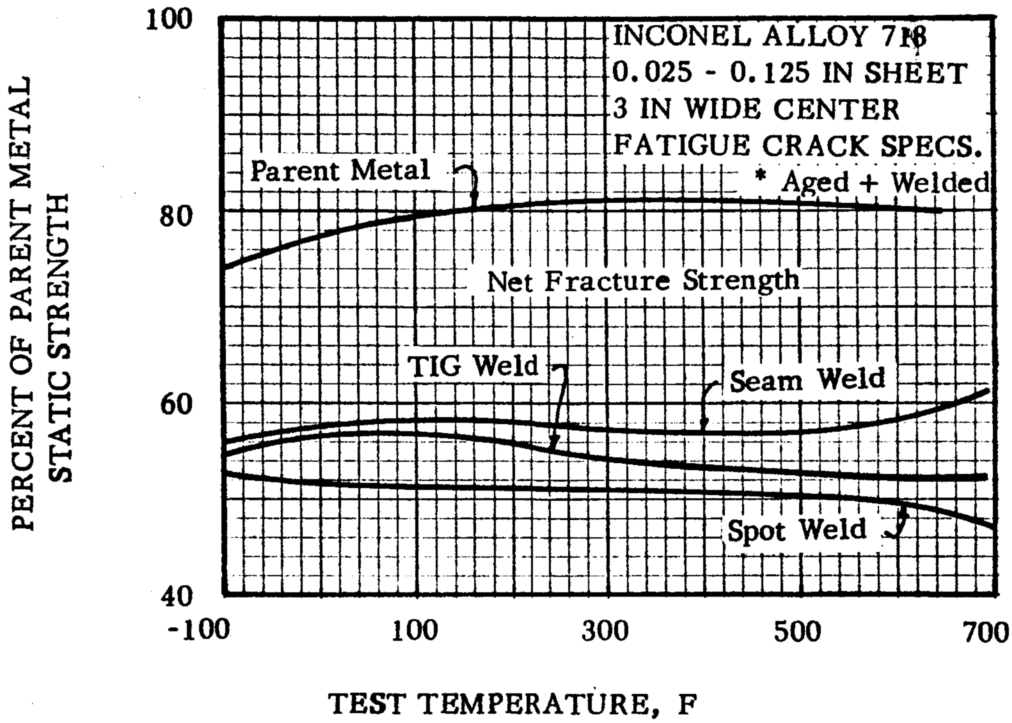

FIG. 12.6 NET FRACTURE STRENGTH FOR VARIOUS WELD PROCEDURES COMPARED TO ORIGINAL PARENT METAL STATIC STRENGTH

(Ref. 12.2)

* CR (20%) + Aged 1275F, 8 Hr, FC 20F/Hr to 1150F, Hold 10 Hr, AC

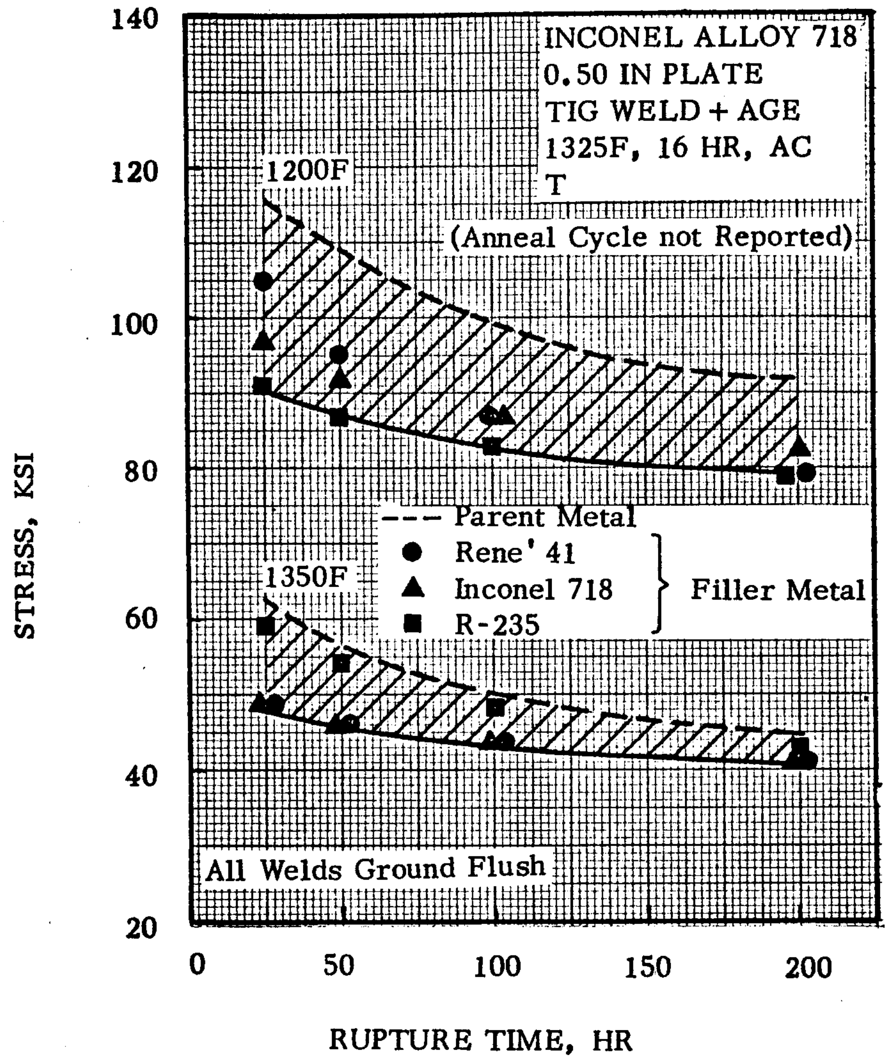

FIG. 12.7 CREEP RUPTURE DATA FOR PLATE TIG WELDED WITH VARIOUS FILLER METALS

(Ref. 12.9)

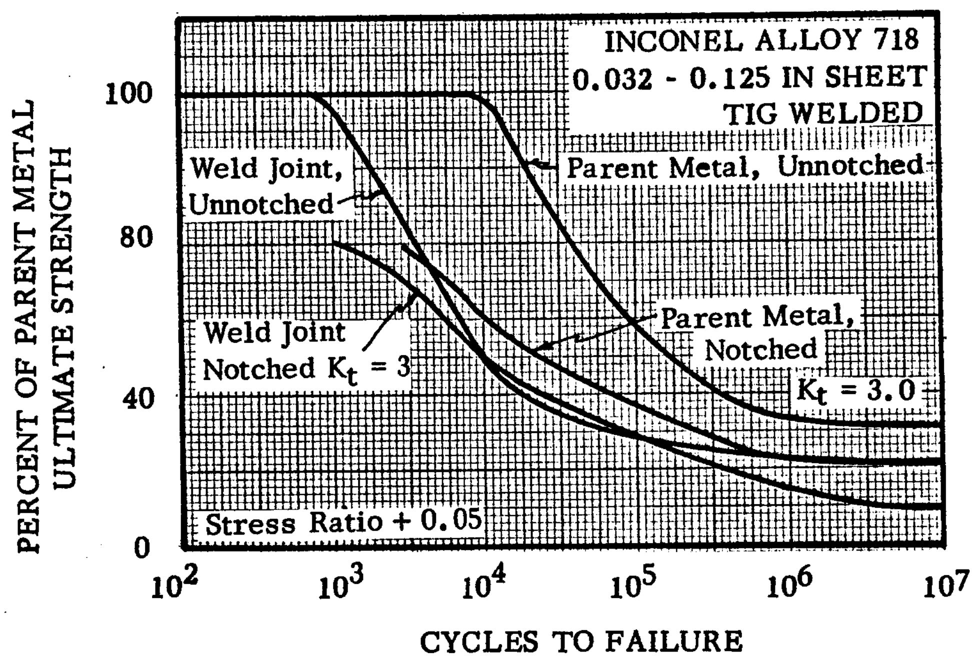

FIG. 12.8 AXIAL-TENSION FATIGUE PROPERTIES OF ALLOY PARENT METAL, WELD JOINT AT ROOM TEMPERATURE

(Ref. 12.1)

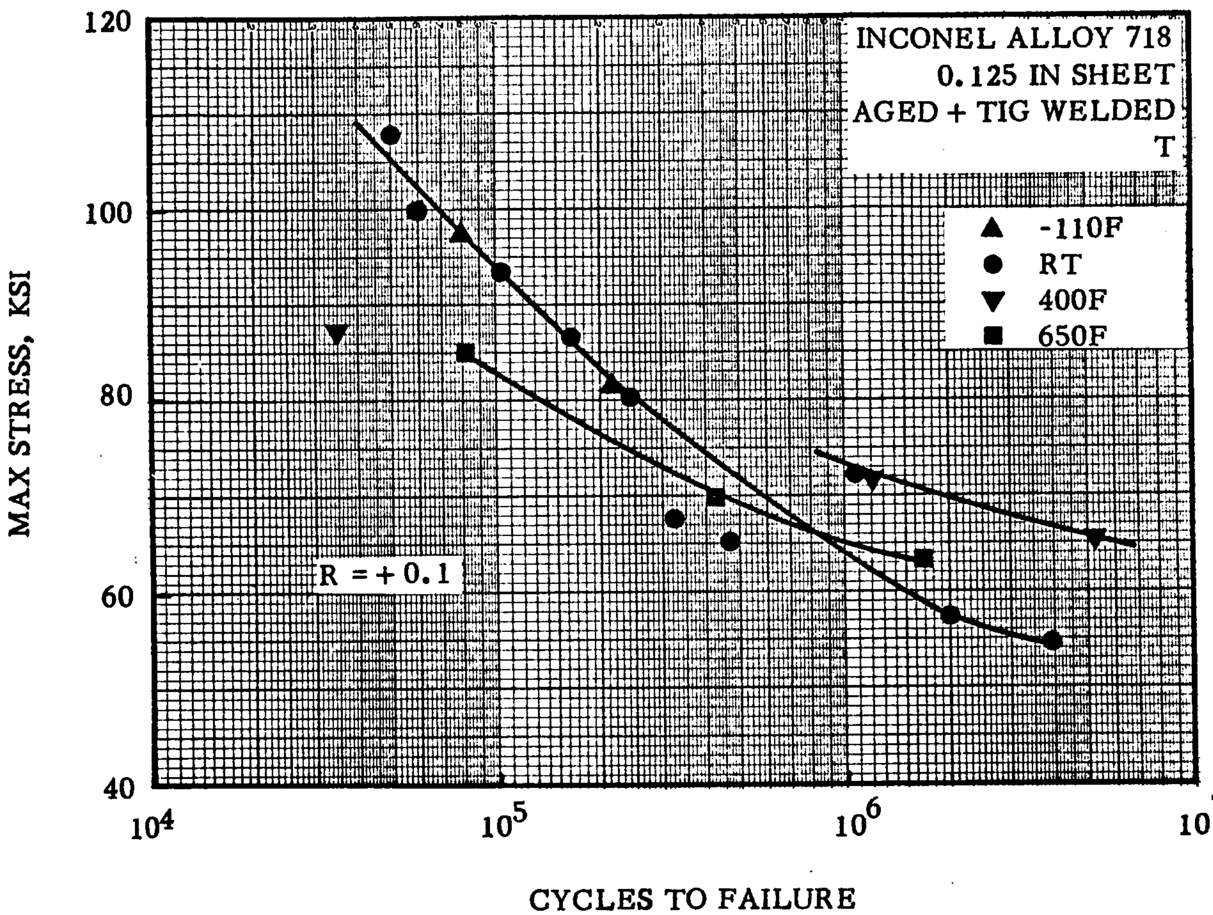

FIG. 12.9 FATIGUE STRENGTH OF TIG WELDED SHEET AT VARIOUS TEST TEMPERATURES

(Ref. 12.2)

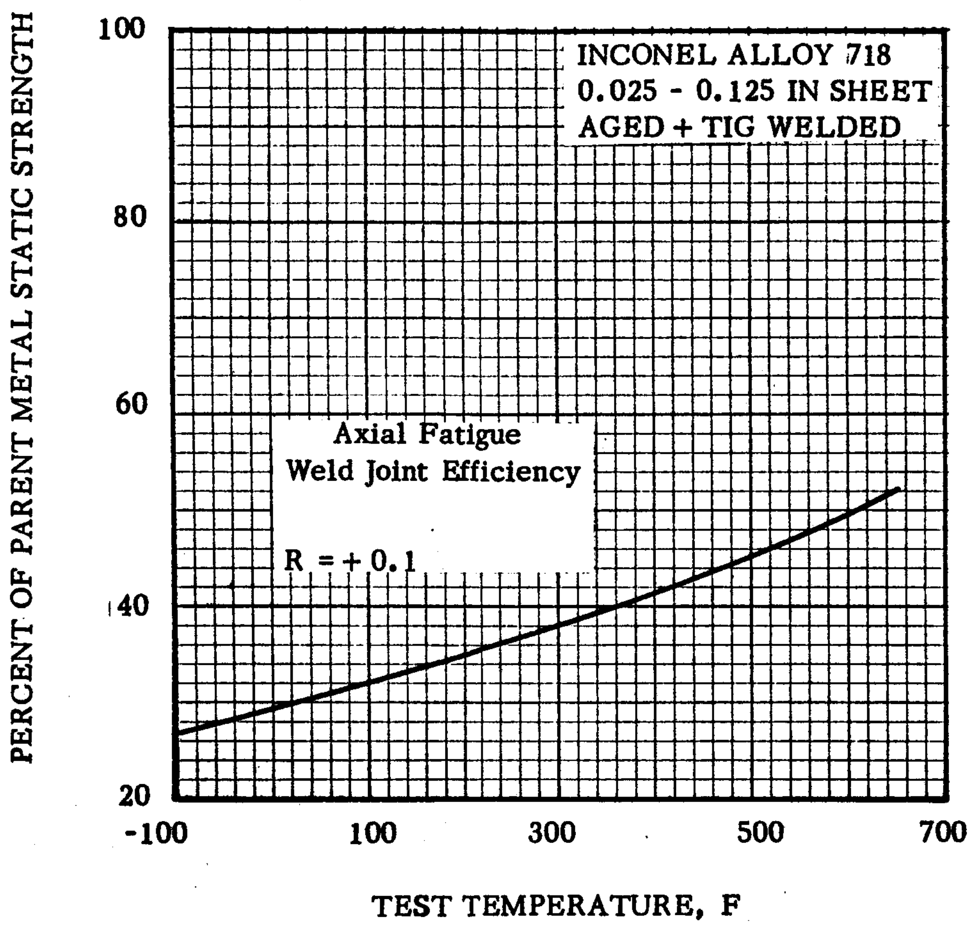

FIG. 12.10 AXIAL-FATIGUE TIG WELD JOINT EFFICIENCY AT VARIOUS TEST TEMPERATURES

(Ref. 12.2)

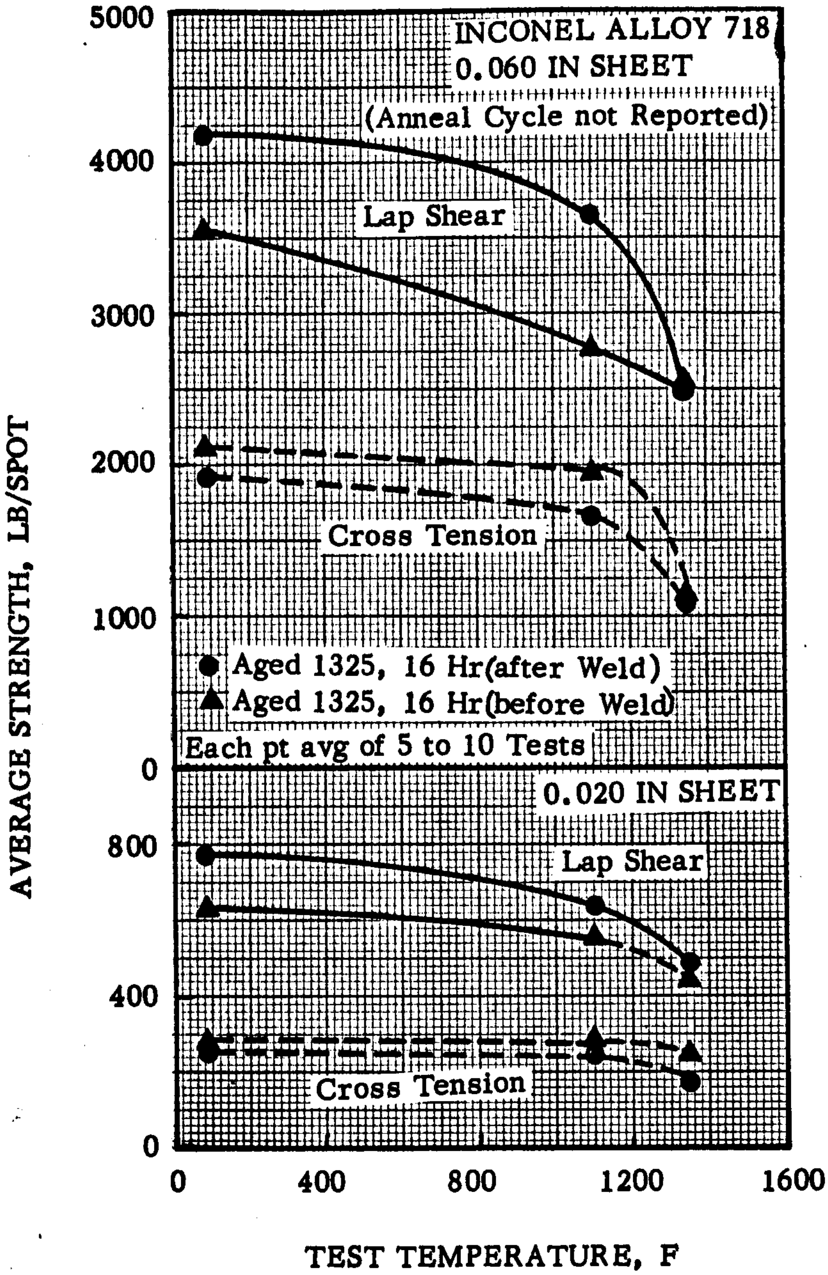

FIG. 12.11 SINGLE SPOT WELD LAP SHEAR AND CROSS TENSION DATA AT 80, 1100 AND 1350F

(Ref. 12.10)

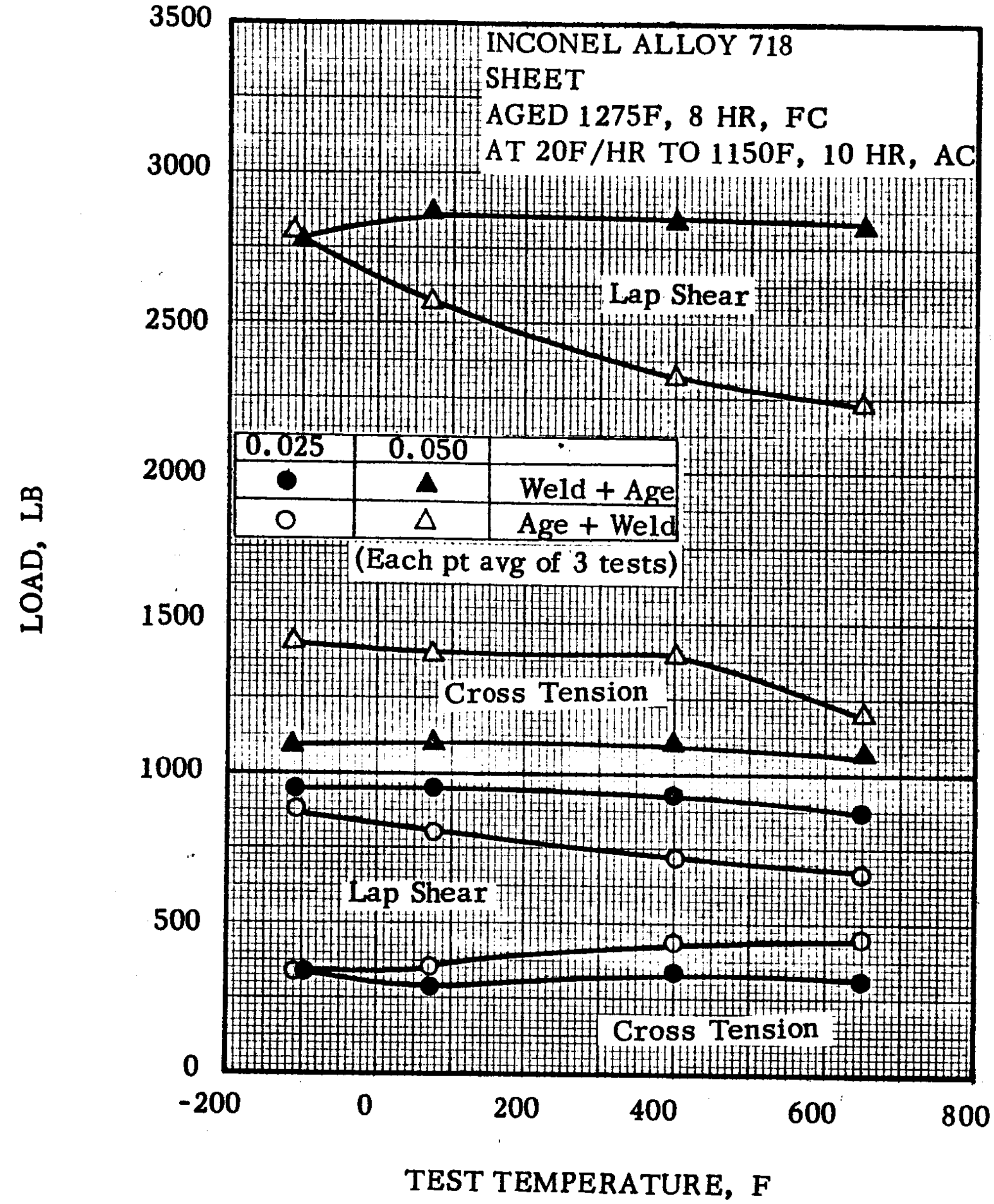

FIG. 12.12 SINGLE SPOT WELD LAP SHEAR AND CROSS TENSION DATA AT VARIOUS TEST TEMPERATURES

(Ref. 12.2)

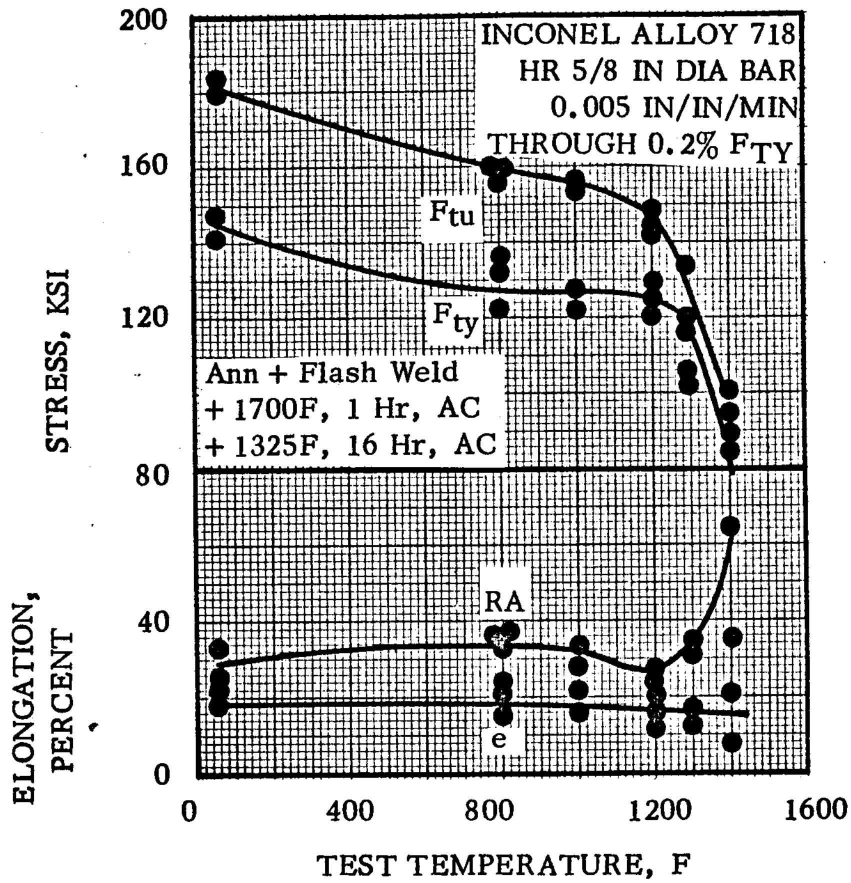

FIG. 12.13 EFFECT OF ROOM AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF FLASH WELDED BAR

(Ref. 12.1)

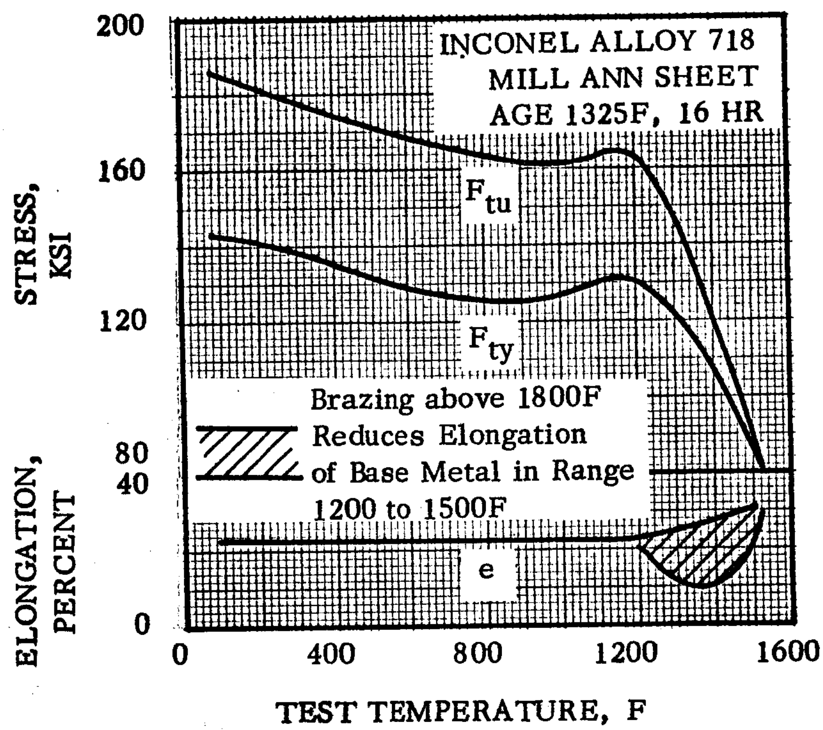

FIG. 12.14 EFFECT OF ROOM AND ELEVATED TEMPERATURE ON TENSILE PROPERTIES OF SHEET AND EFFECT OF BRAZING ON ELONGATION

(Ref. 12.9)

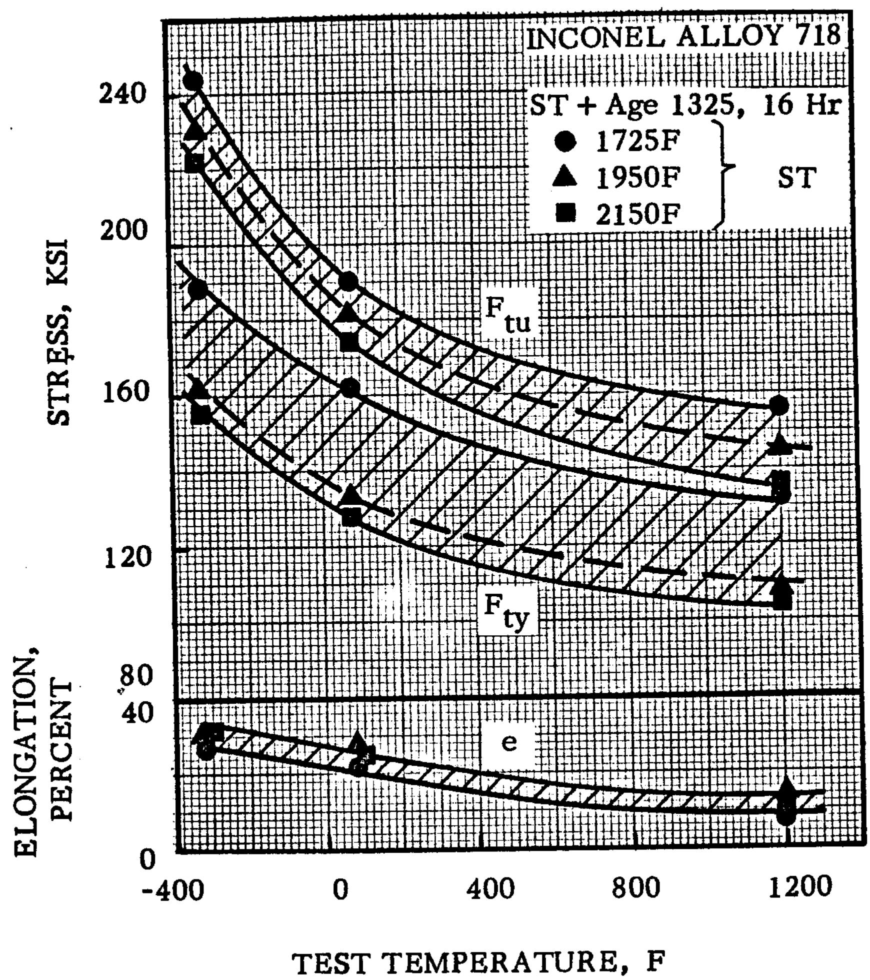

FIG. 12.15 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF ALLOY FOR VARIOUS SOLUTION ANNEAL TEMPERATURES

(Ref. 12.1)

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